A critique of the chronometric evidence for hominid fossils: I. Africa and the Near East 500–50 ka

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Abstract

The chronometric dating evidence for all hominid fossils from Africa and the Near East that have previously been dated to 500–50 ka is critically assessed using the concept of chronometric hygiene, and these dates are revised using Bayesian statistical analyses where possible. Sixteen relevant hominid sites lacking chronometric evidence are briefly discussed. Chronometric evidence from 37 sites is assessed in detail. The dates for many hominid fossils are poorly constrained, with a number dated by comparisons of faunal assemblages—a method that does not have good chronological resolution for much of the last million years. For sites with stratigraphic sequences of dates, it is generally possible to refine the dating, but in some cases, the revised chronology is less precise than previous chronologies. Fossils over 200 ka in age tend to be poorly dated, but for the last 200 ka, dating is better due to the availability of electron-spin-resonance and thermoluminescence dating. Consideration of the chronologies favored by the proponents of the out-of-Africa and multiregional hypotheses of human evolution shows their selectivity. The chronological assessment of the fossils here is compatible with either hypothesis. If evolutionary schemes that do not rely on the morphology of the hominid fossils to decide the sequence of fossils are to be built, then further dating is required, alongside full publication of existing dates.

Introduction

Our understanding of the early evolution of *Homo sapiens* depends critically on being able to define the chronology and ordering of middle and late Pleistocene (ca. 500–50 ka) sites containing hominid fossils and/or archaeological evidence for "modern human behavior." Although there have been numerous attempts to date (and redate) key sites, the "most serious impediment to interpretation of the Middle Pleistocene record has been the lack of a sound chronological framework" (McBrearty and Brooks, 2000: 487). The provision of a reliable chronology is a key component required in the resolution of conflicting theories of modern human origins and dispersal. Over the last decade, the majority of opinion on the evolution of modern humans has favored the out-of-Africa model of human expansion at ca.100 ka replacing earlier hominids, rather than the multiregional model of worldwide evolution with gene flow. However, debate continues (Cann, 2002; Templeton, 2002; Thorne and Wolpoff, 2003; Bräuer et al., 2004), with the details of both models contested, though there is more extensive debate within the out-of-Africa school (e.g., McBrearty and Brooks, 2000). Within these debates, some dates on fossils are widely accepted (e.g., dates of ca. 100 ka for modern humans in the Levant), while others are disputed or uncertain so that different authors choose different chronologies to suit their evolutionary schemes. The debates will not be resolved until we have clear knowledge of which fossils' dates are and are not well constrained, as well as the reliability of these dates. Genetic studies provide some evidence, but are inherently ambiguous in their dating (Cann, 2002; Templeton, 2002). Other aspects of the study of human evolution, such as brain size and cognitive capacity (Aiello and Wheeler, 1995; Mithen, 1996) and the impact of climate change (Ambrose, 1998) also rely on being able to date fossils firmly. The crucial importance of dating evidence has led to a great deal of effort being expended over the last 20 years in obtaining and improving chronometric dates for fossils (e.g., Aitken et al., 1993). As dating procedures have evolved, it has become clear that some methods are more reliable than others, and all have significant uncertainties in their estimates. Despite this fact, many authors treat dates uncritically or selectively. Some choose "the most likely ages" (see caption to Figure 1 in Bräuer et al., 1997) or ignore the published uncertainty in chronometric estimates, leading to overinterpretation of the dating evidence. Others ignore known technical problems that suggest certain types of dates are unreliable (Millard and Pike, 1999). Even the recent compilation of dates for African hominids (see Table 1 in McBrearty and Brooks, 2000) suffers from each of these errors in several places, despite its greater awareness of the problems than many other papers. Hence, there is a need for the development of a methodology for systematic and coherent evaluation of dating evidence, and its application to fossil hominid sites, before dating evidence can be used to support or refute particular interpretations of human evolution.

Archaeologists and geologists have recognized for many years that chronometric dates and stratigraphic information need to be combined, if only at the level of establishing that the ordering of samples according to stratigraphy agrees with their ordering by chronometry. The last 15 years have seen the development and application of Bayesian statistics to radiocarbon calibration and chronological modeling as a means to move beyond this level so that the stratigraphic (or other) prior chronological information can be used to constrain and inform the quantitative estimates of time from chronometric measurements. In general, this approach leads to gains in chronological resolution, and fuller statements of uncertainty, due to the use of all available information. Until recently, radiocarbon dates were the only chronometric data that could be incorporated using this methodology (Buck and Millard, 2003). This paper uses recent developments in this methodology that allow luminescence, uranium-series, and electron spin resonance (ESR) dates to be included in stratigraphic analysis, and applies them to test and refine the age estimates for hominid fossils from the period of 500–50 ka, within which modern human skeletal morphology appears.

Methods

Two basic principles underlie the methods used here:

(1) "chronometric hygiene" (Spriggs, 1989) should be applied to all dating techniques and samples;

(2) wherever possible, all chronometric information should be treated within a coherent analytical framework (including statistical analyses) with internally consistent assumptions.

Chronometric hygiene

Chronometric hygiene seeks to weed out from our collection of dates those that are unreliable or unrelated to the question at hand before analyzing the remainder. The idea of applying such a sifting process to the dates relating to hominid fossils is not new, as a scheme for the general classification of the reliability of dates and their association with fossils was set out by Oakley (1964), and a detailed scheme for critical consideration of radiocarbon dates was described by Waterbolk (1971) and more recently by Pettit et al. (2003). The caveats and criteria for reliability of other dating techniques are less explicitly set out in the literature. For the methods considered here, criteria for technical reliability are outlined below, and a more detailed discussion of critical approaches to assessing the reliability of dates will be found in a forthcoming volume (Bailiff and Millard unpubl. ms.), including indications of what data should be published to allow for a critical assessment and, if required, recalculation of dates based on different assumptions. In general, chronometric hygiene assesses the extent to which the samples conform to the assumptions of the technique, the consistency of repeated measurements on the same sample, and the consistency of sequences of dates with their stratigraphic order.

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Potassium-argon (K-Ar) and argon-argon (Ar-Ar) dating methods rely on assumptions of release of Ar during melting of minerals and of initial ^{40}Ar content prior to the build up of radiogenic ^{40}Ar from the decay of ^{40}K. These are critical considerations for both methods, but they are hard to test with K-Ar dating except by consistency within groups of ages, and between K-Ar ages and those obtained by other methods. With Ar-Ar dating, however, stepwise heating and single-crystal laser-fusion (SCLF) allow the assumptions to be tested, using plateau tests, age spectra, and isochrons (McDougall and Harrison, 1988). For the young subaerial samples of most middle and late Pleistocene hominid sites, isochrons should show initial $^{40}Ar/^{39}Ar$ ratios close to the atmospheric value of 295.5 (Steiger and Jäger, 1977), and age-spectra or plateau tests should show a strongly reproduced young age with some higher ages if the sample is incompletely reset.

Most Ar-Ar ages considered here are SCLF ages. The methods reported in the literature for assessing the consistency of such dates on the crystals of a single sample are ad hoc and variable. McDougall et al. (2005) rejected outliers that are more than two standard deviations (SD) from the mean, iterated until no more analyses were rejected, and then calculated a mean age from the remaining analyses. Potts and Deino (1995) also used an iterative process of eliminating the outliers in an ischron analysis until the scatter was accounted for by analytical error alone. Clark et al. (1994) rejected outliers on the basis of visual inspection of age-probability spectra to ensure a normal distribution of results. Potts and Deino's (1995) process is an objective one that does not depend on the number of measurements, but McDougall et al.'s (2005) method will reject 5% of genuine measurements and, like Clark et al.'s (1994) process, does not apply a statistical test showing that the dates accepted and averaged follow the expected normal distribution. Within the field of radiocarbon dating, the standard statistical test for consistency, and rejection of outliers before combining ages, is that of Ward and Wilson (1978). This method tests whether the scatter of a set of dates is greater than that expected if they were normally distributed about a true date with the quoted uncertainties as the only source of scatter. If the test is passed, a weighted mean age and uncertainty are calculated. It thus accomplishes using a formal statistical test what researchers using Ar-Ar dating have attempted using informal approaches. For this reason, Ward and Wilson's (1978) method was used in the present study to reassess the consistency of SCLF measurements of a single sample and to calculate a weighted mean age as the estimate of the age of the sample. For samples failing the test, consideration must be given to alternative methods of calculation. The outlier-elimination method of Ward and Wilson (1978) was used here to reduce the data set to a coherent group that passes the test, but for one site, Bodo, applying this procedure was problematic, and thus a tailored statistical approach was taken, as described below in the discussion of the site. Where there are Ar-Ar dates from multiple samples considered coeval, the Ward and Wilson (1978) test was also appropriate for testing for consistency.

Electron spin resonance (ESR), optically stimulated luminescence (OSL), and, thermoluminescence (TL) techniques have a common basis in measuring a signal that increases in response to environmental radiation while a sample is buried. They differ in the methods of signal measurement and the mechanism for its initial zeroing, and in the assessment of internal radiation dose. In evaluating the external dose, it is necessary to consider possible inhomogeneous radiation fields, especially if elemental analyses of sediment are used without in situ γ-spectrometer measurements for comparison. Multiple samples from the same stratum, or even site, may depend on a few evaluations of external dose, so that statistical analysis is complicated by correlation of uncertainties; this is often forgotten when dates are being combined or compared (Millard, 2003). In addition, where dating is conducted on museum specimens excavated many years ago, careful consideration must be given to the reconstruction of the external dose rate and whether it can be made reliably from small amounts of soil adhering to the sample (Mercier et al., 1995). This is true for all three methods, but in practice applies more to ESR dating studies.

When ESR and luminescence dates on a single stratum were combined in a single chronology, the external radiation field will have been the same for all the samples, and thus it was necessary to check that the various dates were computed using the same values of the parameters that influence that radiation field (i.e., the radiation emitted by the sediment, the water content that attenuates the radiation, and the dose rate from cosmic rays). Where different workers used different assessments or estimates of these parameters, it was necessary to assess the values used, evaluate the means by which they were reached, and arrive at a common set of parameters that could be used to recompute the dates on a common basis. In general, the most conservative estimates of their uncertainties were used.

It is usually assumed that the uncertainty in water content is normally distributed, but this can lead to negative water contents having nonzero probabilities. As water content is expressed as water per dry weight of sediment, a useful approximation is to treat the ratio as lognormally distributed (Aitchison, 1986). The calculations made here therefore assumed lognormal distributions with the same mean and standard deviation as previously estimated.

Dates obtained by these dating techniques also rely to a greater or lesser degree on conversion factors to calculate dose rates from elemental concentrations. Over the years, these have been revised, and for fine-grained comparisons, it is necessary to recalculate ages using the latest tables of conversion factors. For this study, where possible, the tables of Adamiec and Aitken (1998) and Brennan and Lyons (1989) were used to recalculate ages, superseding the tables of Bell (1979) or Nambi and Aitken (1986), and Valladas (1988) or Zimmerman (1972), respectively.

The standard procedure for combining either TL or OSL dates, assuming they date the same event, is that of Aitken (1985: Appendix B), which weights by the uncertainties unique to each sample and accounts for uncertainties in common between samples. There are no published methods specifically for combining ESR dates, and the usual approach has been to average a set of dates, weighting by their uncertainties, and computing a reduced uncertainty (e.g., Grün and Beaumont, 2001). Multiple determinations on one specimen are averaged in the same manner as determinations on multiple specimens. This approach ignores the fact that a major source of uncertainty on all determinations from one specimen, and often on all those from one stratum, is from their common estimates of external dose rate and the sediment water content. Such uncertainties cannot be reduced by averaging. As the structure of the uncertainties is almost identical to that of TL and OSL, the method of Aitken (1985: Appendix B) is more appropriate, but has only occasionally been used. Due to the complexity of the calculation of uncertainty in TL, OSL, and ESR dates, no statistical tests have been devised to check the consistency of a set of dates presumed to be dating the same event.

Electron-spin-resonance dating is usually applied to tooth enamel (Rink, 1997). The technique relies on the measurement of the ESR signal that increases in teeth in response to irradiation. In addition to the external radiation dose, consideration has to be given to the internal radiation dose, which varies with the history of uranium uptake into the tooth. As this history is unknown, it is common to make alternative calculations for two scenarios: early uptake (EU) and linear uptake (LU), which are regarded as extremes of the range of possibilities, representing uptake of uranium immediately after burial (for EU) or steady accumulation of uranium between burial and the present (for LU). If a uranium-series date is also measured on the tooth, it can be used to check which uptake model is more appropriate or allow for the application of a more flexible uptake model such as the US-ESR model (Grün et al., 1988). These more sophisticated (and mathematically more complex) uptake models have not yet been adapted for the Bayesian statistical approach described below, so the analyses of this paper used only EU and LU, noting whether these dates differ from published US-ESR dates. In order for reanalysis of dates to take place, a large number of experimental measurements for each sample must be published, and this is usually the case (Millard, 2006a). In order to use the most recent conversion factors , all ESR dates and their components were also recalculated using ROSY version 2.0 (Brennan et al., 1999; Kao et al., 2003). Where there was no strong evidence as to whether EU or LU ESR dates are more accurate, alternative chronologies are presented for both models.

Optically stimulated luminescence dating (or simply “optical dating”) relies on the removal of OSL signal by bleaching with sunlight, and the stability of any subsequently acquired signal until laboratory measurement. Chronometric hygiene therefore requires the passing of tests for incomplete bleaching or the presence of completely unbleached grains (e.g., Roberts et al., 1999) using multiple aliquots of the same sample or measurements on single grains (e.g., Jacobs et al., 2003b). The OSL signal of quartz grains is generally believed to be stable on Pleistocene timescales, but feldspars often suffer from anomalous fading (Roberts, 1997). Therefore reliable dates are obtained when only quartz is extracted, or when tests show that any feldspars present do not suffer from anomalous fading.

Thermoluminescence dating is best applied to heated materials, notably burnt flints in hominid sites. It is less reliable when applied to unburnt sediments, especially in comparison to OSL, due to the greater chance of incomplete bleaching of the TL signal and greater difficulty of detecting this (Spooner, 1998). The older the material to be dated, the greater the need to check for the onset of saturation of the TL signal, especially as dating moves into the hundreds of kiloannum range.

Uranium-series (U-series) dating is applicable to a range of calcareous materials. It assumes that uranium is present initially without its radioactive decay products (thorium and protactinium) and that no uranium is subsequently lost or gained except by radioactive decay. The build up of the decay products can thus be used to calculate the age of the material. For speleothems, pure calcitic material is preferable, but “dirty” calcites can be dated if account is taken of the initial presence of detrital thorium using a suitable method such as an isochron plot (Ludwig and Titterington, 1994). Bones and teeth have frequently been dated, but it is now clear that they take up uranium continuously and checks on the uranium-uptake history are essential (Millard and Pike, 1999), and methods should be used that allow modeling of that history (Millard and Hedges, 1996; Pike et al., 2002). In comparison with other dating techniques, the majority of U-series dates on bones are underestimates (Millard, 1993: 29). Mollusc shells similarly suffer from unknown uptake histories, and there are fewer methods to control for them than with bone. Uranium-series dates on molluscs are therefore suspect, and as stratigraphic consistency within a site is a necessary but not sufficient criterion for reliability, they are useless for constructing chronologies, as it cannot be determined whether they over- or underestimate the true age. Thus, chronometric hygiene requires all U-series dates on molluscs to be rejected and those on bone to be treated as suspect and likely to be underestimates unless there is a clear understanding of uptake history. Dates on calcitic materials should only be accepted when there is negligible detrital thorium, or when initial thorium is accounted for using an isochron.

No statistical test is currently available to check the consistency of repeated U-series dates on the same sample, due to the nonnormal distribution of uncertainty on these dates. Comparisons were therefore made less rigorously on the basis of overlap uncertainties at two standard deviations.

In addition to criteria relating to the chronometric data, stratigraphic data need to be subject to what might be termed "stratigraphic hygiene" in order for a reliable chronology to be constructed:

(1) the stratigraphic position of the hominid remains and of the dating samples should be securely known and clearly reported;
(2) the stratigraphic relationship between the dating samples and hominid remains should be similarly known;
(3) there should be a correlation of dates with depth and/or stratigraphic ordering, making due allowance for the uncertainty estimates on the dates.

The dating of one deposit often depends on correlation with strata at another location, either within a site, across a region, or even across a whole continent. Within-site correlations are usually clear and uncontentious. Regional correlations are more difficult to prove. Tephra horizons provide good markers (especially in eastern Africa), but their chemical and physical properties are not always unique (Faupl et al., 2003), leading to occasional ambiguity. Regional- and continental-scale correlations are frequently by biostratigraphy, which can introduce even greater ambiguity. It must be assumed that faunal change over distances of up to thousands of kilometers was synchronous and that the current set of dates on faunal assemblages of a particular biochronozone accurately represents its duration. It is certainly not true that a single date at a single site can be directly transferred to all other sites with closely similar faunal assemblages as though a biochronozone had no duration. Biostratigraphy thus gives a good check on chronometric determinations, but on its own it can only provide broad temporal correlations.

In addition to the criteria for reliable dates, where parameters used in the dating calculations might be chosen differently or revised in the future, the chronometric data should be given in sufficient detail to allow recalculation of the dates. In this study, dates were recalculated from published data, as described in the original papers, and any discrepancies were noted. This was necessary as miscalculations occasionally occur.

Statistical approach

In reanalyzing published dates that satisfy the criteria of chronometric hygiene given above, this study attempts to quantify the range of possible dates of each specimen by modeling the relation of hominid remains to dated materials using a Bayesian statistical framework (Christen, 1994; Litton and Buck, 1995; Zeidler et al., 1998; Christen, 2001; Buck, 2003). The Bayesian approach to statistics is framed as taking a current state of knowledge, specified as a prior probability distribution, and updating that knowledge with observations to arrive at a revised state of knowledge, specified as a posterior probability distribution. In an analysis of chronology, the stratigraphic evidence is taken as the prior information and is updated with chronometric data to provide posterior information. Thus, the key feature of this framework is that it combines two forms of dating evidence:

(1) the stratigraphic order of a sequence of events;
(2) chronometric age estimates of those events.

The integration of these two forms of evidence allows:

(1) refined estimates of the date of events included in the analysis;
(2) the estimation of the date of any other event that can be included in the stratigraphic ordering.

In order to do this, mathematical and statistical relationships between the dates of all of the events have to be specified

As most hominid remains are not directly dated, but dated via stratigraphic relationships to directly dated samples, this is a powerful tool to assess the uncertainty of our knowledge about hominid fossils. The stratigraphic relationships between hominid fossils and dated sample are varied and can be complex. However, the possible stratigraphic relationships can be expressed using a small number of components that express the minimum information to record the whole stratigraphic sequence (Harris, 1989). Similarly a small number of components can be used to build mathematical models of stratigraphic orderings. For the purposes of this study, three cases of stratigraphic relationships are important, and their analysis can be contrasted with previous approaches to the process of data reduction required to estimate a fossil's date.

Case 1: Where there are two dates from samples stratigraphically above and below a hominid fossil, the date of the fossil must lie between them. Traditional approaches have not usually attempted data reduction in this situation. The Bayesian approach is to construct a mathematical model expressing the stratigraphic sequence. The simplest model assumes that a priori the true dates of deposition of the fossil and of the two dating samples are each equally likely to lie anywhere in a large time span, subject to them being in the correct order (Buck et al., 1994). As the probability of deposition is the same throughout this period, it is represented by a uniform probability distribution and known by the shorthand label "uniform prior." The prior information on the dates is thus vague and contributes little to the results. Once the chronometric determinations have been obtained, the information on the dates is greatly increased. A simple stratigraphic sequence such as this is found at Lainyamok (see below for details of the dating), where Potts and Deino (1995) simply stated the bracketing ages, but a Bayesian analysis yields a numerical estimate of the date of the fossil itself.

Case 2: A hominid fossil comes from a stratum with a number of dated specimens. Previously, the approach to this situation has been to average the dates to give a "best estimate" of the date of the fossil. However, this yields an estimate of the average date of the stratum, with an uncertainty on that average. If the stratum was deposited over an extended period of time, then this average date may not be close to that of the fossil and the uncertainty of the date of the fossil is underestimated. The Bayesian approach to this situation is to model the deposition of the stratum as a period with events marking the start and end of deposition, both equally likely a priori to have true dates lying anywhere in a large time span, subject to them being in the correct order . Within this stratum, the deposition of the fossil and the dating samples are assumed a priori equally likely to have occurred at any point between the start and end, but there is usually no stratigraphic constraint on their order (Zeidler et al., 1998). In this case, there are two uniform priors: one on the start and end dates, and a second-level one on the events between those dates. From the observed dates within the stratum, the start and end dates are estimated, and thus the date of the fossil that lies between them. The site at Taramsa has a stratigraphic sequence equivalent to this case, where averaging obtained a quite precise age of 63–48 ka, at 95% probability (Vermeersch et al., 1998), but the application of a Bayesian approach yielded a range of 73–40 ka (see below for full discussion of the site).

Case 3: Where a hominid fossil is directly dated or dated by a contemporary specimen, this date is usually quoted as the date of the fossil without considering whether it can be refined by comparison with other stratigraphically related dates. The Bayesian approach incorporates the date into the type of analysis described above to arrive at an improved estimate.

Other more complex stratigraphies can generally be represented in terms of combinations of the above cases. For example, where there are three conformable strata, labeled I, II, and III with increasing depth, with multiple dated samples from Strata I and III, and a hominid fossil from Stratum II, each stratum can be modeled as in Case 2, but with the additional constraint that the end of Stratum III is the same date as the start of Stratum II and likewise for Strata II and I. Most sites considered here have stratigraphic sequences like this with conformable strata in one continuous sequence, and they are modeled in this way. A few are simpler and modeled as in Case 1, and a few are more complex.

If the published dates and stratigraphic information were all that was required to construct Bayesian statistical models to estimate the dates of hominids, then OxCal (Bronk Ramsey, 2001) could be used for the calculations. OxCal is software primarily designed to calibrate radiocarbon dates and incorporate them into Bayesian stratigraphic models, but it can also include results from other techniques as dates with independent, normally distributed uncertainties. However, the dating techniques typically used on Pleistocene sites do not have normally distributed uncertainties and, as discussed above, ESR and luminescence dates often have components of their uncertainties that are common between samples and are thus not independent. The methods of Millard (2006a,b) are necessary to account for uncertainties that are correlated and/or not normally distributed.

Bayesian models of chronologies are not without their problems. In cases where there is a lot of dating information, the results depend only weakly on the assumptions embedded in the model of stratigraphy, but in cases where there are few dates or the intervals between events are comparable to the uncertainties in the dates, the effects of these assumptions need to be assessed (Steier and Rom, 2000; Nicholls and Jones, 2001). In addition, although the models capture the important information from stratigraphy of ordering events in time, this is done at the cost of introducing explicit statistical assumptions. The uniform prior is a repeated and statistically simple assumption, but Nicholls and Jones (2001) showed that it implies a priori that long durations between events are much more probable than short ones. Usually, this has little effect on the results, as the chronometric data constrain the duration between events much more strongly than the prior stratigraphic model, but in situations with complex stratigraphic models and few chronometric data, it can affect the results. This problem can be overcome by taking a mathematically (and computationally) more complex prior assumption that all durations of deposition are equally likely. This is available as an option in OxCal (Bronk Ramsey, 2001), and known as a "uniform span prior," but it was not used for the analyses for this study, except where noted. A uniform prior or a uniform span prior is a necessary but arbitrary assumption that converts a stratigraphic statement about ordering into a quantified probability of a chronology so that it can be linked to quantitative chronometric data (Steier and Rom, 2000). Thus, in applying these stratigraphic models it is important to be aware of the effects of these assumptions and, when needed, to compare alternative models. Nevertheless, the Bayesian methodology for incorporating stratigraphic information gives a powerful means to assess the dates of fossils themselves rather than just the dates of associated materials that are often discussed in vague terms or as if they are direct dates on the fossils.

The results of Bayesian calculations are reported here as 95% posterior probability ranges for the age of the event, given the stratigraphic model and chronometric data. Where only a minimum (or maximum) date can be calculated for a fossil hominid, a range cannot be given, and the most useful representation of date in these cases is the date that has a 95% probability of being a terminus ante quem or terminus post quem for the fossil.

Computation

Where Bayesian stratigraphic models were used, dates were initially recalculated without stratigraphic constraints and compared to the published results to check for gross discrepancies and coding errors. They were then calculated incorporating the stratigraphic constraints as discussed below for each site. Where dates in a sequence were independent (or almost so) and could be represented as normal distributions, calculations were performed in OxCal 3.10, entering the dates as calendar dates. Where the situation was more complex (e.g., where dates were dependent on common external dose-rate estimates), the stratigraphic model and chronometric data were combined using a program coded specifically for the site using WinBUGS 1.3 or 1.4 (Lunn et al., 2000; Spiegelhalter et al., 2004) following the methods of Millard (2006a,b). Computer files for models are available from the author upon request. On occasion, information was not published fully enough to allow for reanalysis of a dependent set of dates, and these sites had to be analyzed as if the dates were independent, while recognizing that such a procedure leads to underestimation of uncertainties.

Results

A number of sites with hominid remains do not have chronometric evidence for their ages. These are summarized with a brief commentary in Table 1. Other sites are presented alphabetically by region for ease of reference. A full list of all chronometric determination used for each site together with the corresponding posterior 95% probability ranges from Bayesian stratigraphic models is given in the online supplementary material.

Olduvai and related sites

The inferred stratigraphic relationships among these sites and a summary of the chronometric evidence is shown in Figure 1.

Bodo, Ethiopia. The hominid cranial and humeral fragments from Bodo are dated to the middle Pleistocene by associated fauna, and a terminus post quem is provided by laser-fusion Ar-Ar dates on a tuff that is lower than the remains by stratigraphic correlation (Clark et al., 1994). The Ar-Ar dates are a mixture of single- and multiple-grain ages and show some contamination by older crystals, complicating their chronological interpretation. Clark et al.

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(1994) preferred the pooled mean age of 630 ± 30 ka, but allowed the weighted mean of single-grain ages of 550 ± 30 ka as a minimum age. Using the Ward and Wilson (1978) methods, the 13 individual laser-fusion ages cannot all be combined to give a pooled mean age, and after the elimination of three outliers, the age is 705 ± 18 ka. However, contrary to the chronometric-hygiene criterion of a strongly reproduced young age, the three laser-fusion ages eliminated are the youngest ages (see supplementary information). A mixture analysis based on the assumption that there are two normally distributed populations of crystals of different ages suggests a younger component with mean age of 523 ± 26 ka and an older component of 725 ± 22 ka. From this and from the calculation on single-grains of Clarke et al. (1994), it seems likely that there is a younger component with an age between 500 and 600 ka, but reliable estimation of its age is difficult with only 13 laser-fusion ages.

Clark et al. (1994) noted the similarity of the Bodo fauna to Olduvai Gorge Bed IV, which is dated to at least 490 ka, and possibly greater than 990 ka (see under Olduvai below). The Ar-Ar date for Bodo, on the basis of any of the interpretations discussed above, lends weight to the short chronology for Olduvai.

Lainyamok, Kenya. Lainyamok is important for its well-dated faunal assemblage and also a hominid femur. The age of the deposits is constrained by K-Ar dates (920 ± 10 ka and 890 ± 30 ka) on the underlying Magadi Trachyte, and SCLF Ar-Ar dates on the volcanic mudflows named Khaki 1 and Khaki 2 (Potts and Deino, 1995). The bones came from the Khaki 2 deposit and are interpreted as having been deposited in hyena burrows in the Khaki 2 layer before subsequent sedimentation, including deposition of Khaki 1 (Potts and Deino, 1995). As the date of the remains is tightly constrained by the Ar-Ar dates, the K-Ar dates do not feature in the analysis here. Using an iterative technique to eliminate outlying (older) results in an isochron

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analysis, and averaging two dates for each layer, Potts and Deino (1995) obtained dates of 330 ± 6 ka for Khaki 1 and 392 ± 4 ka for Khaki 2. Using OxCal, with a model assuming that the hominid femur is a priori equally likely to fall anywhere between these dates, a 95% confidence range for its date of 328–393 ka is obtained.

Olduvai, Ndutu, and Ngaloba (Laetoli), Tanzania. Two hominid specimens that potentially fall into the period reviewed here have been found at Olduvai Gorge, and other specimens have been found in the Ngaloba Beds at Laetoli and at Ndutu, which can be stratigraphically correlated with the Olduvai remains (Leakey and Leakey, 1977; Hay, 1987; Mturi, 1976). The stratigraphic sequence at Olduvai is of Beds I to IV followed by the Masek Beds, the Ndutu Beds, and the Naisiusiu Beds (Figure 1). Tamrat et al. (1995) considered the magnetostratigraphy of the sequence from Bed I to the Masek Beds. They preferred a long chronology, correlating the reversed magnetization of the upper Masek Beds with the end of the Matuyama Chron at 990–780 ka, but allowed that a short chronology was possible, with this reversed magnetization correlating to the Emperor Subchron at about 490 ka and the Brunhes-Matuyama boundary occurring high in Bed IV. Both chronologies place the end of the Olduvai subchron at 1770 or 1790 ka, low in Bed II. Either magnetostratigraphic interpretation is compatible with K-Ar ages on faulting that bracket the formation of the Masek Beds. MacIntyre et al. (1974) reported a mean age of 321 ± 44 ka for flows contemporary with faulting postdating the Masek Beds. They also reported that faulting that predates the Masek Beds is bracketed by faulted flows averaging 1217 ± 22 ka and unfaulted flows averaging 1156 ± 22 ka. The fauna from Bodo (Ethiopia) is similar to that in Bed IV at Olduvai, and dates to less than 646 ± 42 ka, lending weight to the short chronology for Olduvai (see under Bodo above).

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The Ndutu Beds have produced infinite radiocarbon dates from the upper unit (Hay, 1976). The lower unit contains a marker tuff that is correlated to one in the Ngaloba Beds at Laetoli, containing the LH 18 skull (Hay, 1987). Hay (1987) estimated the age of this tuff to be 120 ± 30 ka but gave no basis for his estimate other than "its relative stratigraphic position" (p. 45). At Mumba Shelter, uranium-thorium measurements on bones overlying this tuff provide an apparent age of 132 ± 7 ka (Bräuer and Mehlman, 1988). Similarly, bones from the tuff in the Ngaloba Beds at Laetoli have produced an apparent uranium-thorium date of 129 ± 4 ka (Hay, 1987). Because of uncertain uranium-uptake histories, both of these dates should be regarded as unreliable, but they are probably minimum ages. The Naisiusiu Beds have produced infinite or nearly infinite radiocarbon dates (Skinner et al., 2003), or dates on materials now considered to be unreliable, but recent work has produced LU ESR dates averaging 62 ± 5 ka for the type section (Skinner et al., 2003).

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Thus, the few available dates form a coherent sequence for these sites, but they provide only vague information about the ages of the hominids. While a chronological model could be constructed, the results would be very sensitive to the prior assumptions. More dates are required; nevertheless, the dates for the hominids may be stated broadly as:

(1) for the OH 11 maxilla, attributed to Lower Ndutu Beds (Leakey and Leakey, 1977), >62±5 ka, certainly <990 ka, and probably <490 ka;

(2) for LH 18, in the marker tuff (Hay, 1987), probably >129 ± 4 and >132±7, certainly <990 ka, and probably <490 ka;

(3) the Ndutu cranium underlies a tuff that is probably correlated with the Norkilili (upper) Member of the Masek Beds, which would make it older than LH 18, but the tuff could be

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that in the lower unit of the Ndutu Beds, which would make its possible age range similar to that of OH 11 (Mturi, 1976);

(4) for the OH 23 mandible, from the Lower Masek Beds (Leakey and Leakey, 1977), either 1070–990 ka or (more likely) 780–490 ka.

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Mumba and Eyasi, Tanzania. These two sites are close together and their sedimentary sequences are linked (Mehlman, 1987). The report of initial dating attempts by Protsch (1981) on the Eyasi remains using amino-acid racemization and radiocarbon was shown by Mehlman (1984) to be confused and to suffer from technical deficiencies. These data are not considered here. Mehlman (1987) established the stratigraphic provenance of the surface-collected hominid remains as Member C of the Eyasi Beds. Absolute age constraints arise from an underlying trachytic tuff in Member F, which is regionally correlated with tuffs in the upper Ngaloba Beds at Laetoli and the lower Ndutu Beds at Olduvai Gorge (Figure 1). From uranium-thorium dates on bone at Ngaloba, this tuff has a possible minimum age of 129 ± 4 ka (Hay, 1987) and a maximum age given by a paleomagnetic reversal in the Norkilili Member of the Masek Beds at Olduvai of 490 ka or 990 ka (the short chronology is more likely: see above under Olduvai). A minimum age is provided by dates from sediments at Mumba Shelter, which overlie the Eyasi Beds. There are radiocarbon dates of 26,900 ± 760 BP (ISGS-566 from Bed III) and a stratigraphically earlier date of 25,130 ± 320 BP (USGS-1505 from Bed IV) (Mehlman, 1987). Uranium-series measurements on a bone from Bed VI-B yielded a uranium-thorium age of 132 ka and a uranium-protactinium age of 109 ka (Bräuer and Mehlman, 1988). However, the concordance between the two decay schemes is necessary but not sufficient evidence for a closed system, and U-series dates on bone cannot be relied on without investigation of their uranium-

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Comment [ARM15]: refers to my own argument above uptake history (Millard and Pike, 1999), though they are most likely underestimates of the true age. At Mumba Shelter, three human molars were found in layer VI-B (Bräuer and Mehlman, 1988), and are thus broadly contemporary with the U-series-dated bones. The remains from these two sites are therefore rather imprecisely dated to between 990 ka and 132 ± 7 ka, and more likely between 490 ka and 132 ± 7 ka, with Eyasi older than Mumba.

Other eastern African sites

Aduma, Ethiopia. Haile-Selassie et al. (2004) reported parts of four anatomically modern hominid crania from the Middle Awash region, 15 km from the Herto locality. Comparisons of lithic assemblages suggest that the remains are younger than the Herto formation (Haile-Selassie et al., 2004) and therefore younger than 154 ± 7 ka (see under Herto below). Yellen et al. (2005) reported Ar-Ar dating confirming that the deposits are younger than 180 ka, and various age determinations using U-series, TL, and OSL, which they regarded as problematic. No details of the chronometric measurements were reported, so a critical examination of the dating evidence is not possible. Yellen et al. (2005) considered the OSL ages of 91 ± 5, 93 ± 16, 92 ± 15, and 93 ± 10 ka to be the most reliable and concordant with their set of U-series dates on bone ranging from 79 ± 1 to 105 ± 14 ka. The fossils are therefore broadly dated to 100–80 ka, but not much confidence can be placed on this date.

Garba III, Melka Konture Basin, Ethiopia. Hominid cranial fragments were recovered at Garba III, which is located above all four tuffs in the Melka Konture Basin that can provide stratigraphic correlations (Chavaillon, 1982). The youngest tuff, Tuff D, has normal magnetic polarity and is placed within the Brunhes Chron (Westphal et al., 1979). As there are several phases of sedimentation and down cutting between Tuff D and Garba III, the hominids must be

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considerably younger than the Brunhes-Matuyama boundary at 780 ka (Berggren et al., 1995), but no specific date within the Brunhes Chron can be given.

Herto, Ethiopia. Fossil hominid material assigned to a new subspecies, *Homo sapiens idaltu*, consisting mostly of skulls and skull fragments, was described by White et al. (2003) and dated by Ar-Ar to between 154 ± 7 and 160 ± 2 ka (Clark et al., 2003). The maximum age comes from multiple dates on volcanically derived clasts in the fossiliferous unit, and the minimum age comes from correlation of the overlying Waidedo Vitric Tuff (WAVT) with an unnamed tuff in the Konso region of southern Ethiopia on the basis of geochemical composition. This unnamed tuff underlies the Konso Silver Tuff, which was directly dated by Clark et al. (2003). Faupl et al. (2003) contested the security of the correlation of the WAVT to the unnamed tuff in Konso on the grounds that this geochemical comparison is "highly speculative," (Faupl et al. 2003: 622) as it does not include rare earth elements or isotopes. In a reply, Hart et al. (2003), demonstrated the close geochemical similarity between the two tuffs. There seems to be no evidence against these tuffs being from the same eruption, though stronger correlations could be sought. Ages have been recomputed from the supplementary data of Clark et al. (2003), and analyzed with stratigraphic ordering using OxCal. The resulting date for the Herto remains is 161–150 ka.

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Ileret (Guomde), Kenya. A hominid skull (KMN-ER 3884) and a femur (KNM-ER 999) were recovered from the top of the Chari Member of the Koobi Fora formation (this member was formerly known as the Guomde Formation), close to the base of the Galana Boi Formation, which is latest Pleistocene to Holocene in age (Bräuer et al., 1997). Direct U-series dates by gamma-spectrometry on the bones yielded infinite ages, with a minimum 180 ka (Bräuer et al., 1997). Although this method is not very reliable (Millard and Pike, 1999), the date probably is a minimum. As the remains come from the top of the formation, they must postdate the Silbo Tuff,

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which is dated to 751±22 ka, but there is a stratigraphic disconformity between the Chari Member and the Galana Boi Formation (McDougall and Brown, 2006), and thus the only estimate for the minimum age of the fossil is 180 ka.

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Kapthurin, Kenya. Deino and McBrearty (2002) reported Ar-Ar dates for tuffs bracketing the stratigraphic position of fossils KNM-BK 63 through KNM-BK 67 and KNM-BK 8518. The single-crystal laser-fusion ages on these tuffs are all concordant within a sample and yield an age of 509 ± 9 ka for the overlying Grey Tuff, and 543 ± 4 ka for the underlying K2 Pumice Tuff. A simple stratigraphic model allowing a uniform prior probability that the hominid remains lie between the two tuffs yields an age of 547–501 ka. Deino and McBrearty (2002) argued that, because the remains are known to come from about 0.7 m (KNM-BK 63 through KNM-BK 67) and 3 m (KNM-BK 8518) below the Grey Tuff, the ages may be interpolated. They inferred a sedimentation rate of 1 m/kyr, but did not state the vertical distance between the two tuffs. From Figure 3 of Deino and McBrearty (2002), the distance is about 34 m vertically from the Grey Tuff exposures to the K2 exposure in the Bartekero River valley, but only about 18 m to the exposure in the Kobosowany River valley, which is slightly closer horizontally but in a different direction. Simple linear interpolation between the Ar-Ar ages using a 34 m distance gives ages of 510 ± 9 ka for KNM-BK 63 through KNM-BK 67 and 512 ± 9 ka for KNM-BK 8518. Using an 18-m distance gives ages of 510 ± 9 and 515 ± 8 ka, respectively. Whether taking interpolated dates or the broader dates of the simple stratigraphic model, these mandibles (KNM-BK 67 and KNM-BK 8518) and postcranial fragments (KNM-BK 63 through KNM-BK 65) are some of the most precisely dated hominid remains from the Pleistocene of Africa.

Omo Kibish, Ethiopia. Omo I and Omo II are cranial remains of modern human form that, until recently, were poorly dated (McDougall et al., 2005). Renewed fieldwork in the region

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and new laser-fusion Ar-Ar dates give a more reliable chronology (McDougall et al., 2005). Both remains derive from the upper part of Member I of the Kibish Formation, where they overlie a tuff. A second tuff about 50 m higher, in Member III of the formation, gives a minimum age. McDougall et al. (2005) claimed to have arrived at a consistent set of dates from the multiple laser-fusion measurements on each sample, using iterative elimination of outliers more than 2 SD from the mean. Application of the chronometric-hygiene procedures advocated in this paper to the fully published laser-fusion Ar-Ar dates on multiple groups of 1–6 crystals in pumice clasts yields slightly different results to the original publication (Table 2) and suggests four times as many outliers in the data set. McDougall et al. (2005) combined dates from the three 02-01 samples to arrive at a date for Member I and combined the four 99-275 and 99-274 samples to arrive at a date for Member III. However, application of the Ward and Wilson (1978) statistical test shows that, within each of these groups, the values differ significantly at the 5% level, whether one takes the dates as originally calculated or as recalculated here. If the level of consideration for averaging within either group is taken back to the level of the individual laser-fusion results, then Ward and Wilson's (1978) outlier-elimination method eliminates even more laser-fusion measurements than when it is applied to clasts individually, and this larger group of outliers does not include some of the measurements identified as outliers from individual clasts. Thus, there is not a single coherent date represented by the clasts, and the best estimate of the age of the deposit in which they lie is the age of the youngest clast in each case. On this basis, the hominid remains are dated to between 189.6 ± 1.4 ka (sample 02-01B) and 99.8 ± 1.0 ka (sample 99-274A), but actually lie much closer in time to the former. This is a few thousand years younger than the original publication's range of 196 ± 2 ka to 104 ± 7 ka.

Porc Epic (Dire Dawa), Ethiopia. A fragmentary piece of mandible was excavated in 1933, and on the basis of excavations and subsequent obsidian-hydration dates was assigned a minimum age of 70–60 ka (Clark, 1988). However, Deacon emphasized that the mandible was recovered "from old excavations that lack modern standards of stratigraphic control" (Deacon, 1989:547-548). Assefa (2006) noted that the 1933 discoveries were poorly described and cannot be related to the 1970s excavations that yielded the dated obsidian and gastropod shells with conventional radiocarbon dates from 33,700 ± 300 to >43,200 BP. It seems unlikely that a date more precise than later Pleistocene can be assigned to this fossil.

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Singa, Sudan. The hominid calvaria from Singa has been dated by McDermott et al. (1996). The enclosing calcrete gave one uranium-thorium date of 133 ± 2 ka, confirmed by less precise dates from isochron analyses of other samples of calcrete and from ESR measurements on indirectly associated animal teeth (McDermott et al., 1996). As the calcrete formed after the deposition of the calvaria, this constitutes a minimum age for the specimen.

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Northern African sites

Jebel Irhoud, Morocco. The Irhoud 1–4 hominid specimens are poorly provenanced, but Grün and Stringer (1991) reported ESR ages on three teeth from a level immediately overlying Irhoud 4, which produced five age estimates, though they are reported only as "EU estimates range between about 90 and 125 ka and the LU estimates between 105 and 190 ka" (Grün and Stringer, 1991: 185). These numbers seem to be reflected as error bars in their figure, and it is not clear if these are confidence ranges for averages of the dates or ranges for the midpoint estimates, though the discussion of them by Hublin (1993) implies the latter. Hublin (1993) stated that the three dated teeth are stratigraphically close together and low in the sequence, and thus that the spread of ages is problematic. However, without uncertainties on the dates, it is impossible to assess whether they are statistically different. Amani and Geraads (1993) examined the faunal collection and identified an additional hominid mandible fragment. Their estimate of the age of the site was late middle Pleistocene, with a suggested maximum age of 150 ka. This faunal date is more compatible with the LU ESR date than the EU one, but without more details of the dating, these remains can only be broadly placed as late middle Pleistocene.

Kebibat (Rabat), Morocco. The skull fragments and mandible known as "Rabat Man" were placed by Saban (1977) in the middle Tensiftian (i.e., the middle of the middle Pleistocene) between his assignments of Sidi Abderrahman to the early Tensiftian and of Thomas Quarries and Salé to the late Tensiftian. The reasons for this placement are not fully detailed in his paper. There are U-series dates by Stearns and Thurber (1965) on molluscs; however, these were published in the very early days of U-series dating before the unreliability of dates on molluscs was recognized. Thurber himself later coauthored a paper reviewing U-series dates on molluscs, including these, which concluded that they were all suspect until the uranium-uptake process in molluscs are understood (Kaufman et al., 1971). Nothing more precise than a middle Pleistocene age can be assigned.

Mugharet el Aliya (Tangier, Morocco). Three hominid teeth and a juvenile maxilla were found in Aterian contexts at this cave site, and probably originate in Layer 5 (Wrinn and Rink, 2003). One ESR date has been obtained for each of layers 10, 9, 6, and 5, with the hominids coming from the highest dated layer. Recomputation of the ESR dates of Wrinn and Rink (2003) shows that the gamma-dose rate from the sediment seems to have been miscalculated. For samples 97121a–97123a, the reported dose rate equates to that computed using the conversion factors of Nambi and Aitken (1986) without any attenuation due to water, rather than with

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Taramsa, Egypt. A child's skeleton in a burial was recovered from Middle Paleolithic quarry deposits (Vermeersch et al., 1998). The sequence of OSL dates for the quarrying are inadequately reported for a full model to be constructed. The dates are all associated with late Middle Paleolithic contexts, as is the child's burial. Vermeersch et al. (1998) averaged a wide range of imprecise dates to obtain a date of 55.5 ± 3.7 ka. Using a model in OxCal that treats all of the dates and the skeleton as coming from a single coherent phase of deposition yields a date of 72.9–40.7 ka with a uniform prior or an almost identical date of 72.7–40.7 ka with a uniform span prior. As the dates have not been fully modeled, the uncertainties are underestimated.

Southern African sites

Blombos Cave, South Africa. Nine human teeth have been recovered from a number of different Middle Stone Age (MSA) strata at Blombos (Henshilwood et al., 2001; Grine and Henshilwood, 2002). From the MSA levels, there is one reported date of 103 ± 9.8 ka from the uppermost level, using a subtraction technique combining TL of quartz and infra-red stimulated luminescence (IRSL) of feldspars to overcome changes in environmental radiation dose rates (Vogel et al., 1999; Henshilwood et al., 2001). However, Henshilwood et al. (2001) considered this date to be unreliable because there is evidence that the sample contained spalled cave-roof material as well as aeolian grains. Overlying the MSA levels is an aeolian sand layer, which also

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found outside the cave. This has been dated by OSL using both multiple-grain aliquots (Jacobs et al., 2003c) and single grains (Jacobs et al., 2003a,b). The two approaches yield equivalent results within their uncertainties. The multiple-grain-aliquot dates are based on the measurement of a much larger number of grains and are therefore more reliable, given that the single-grain approach showed the suitability of the samples for OSL dating.

Based on a model of the sand deposition in a single event, the three OSL dates can be averaged to give a minimum age of 70.1 ± 1.9 ka (Jacobs et al., 2003c), which can be expressed as a 95% probability that the remains are older than 67.0 ka. Alternatively, it is possible to consider these three OSL dates to represent a phase of deposition and calculate an age for the start of the phase of deposition that represents the minimum age of the deposits. As the majority of uncertainty in the three dates is independent, it is feasible to calculate this by entering them as calendar dates in OxCal to give an alternative minimum age of 69.0 ka at 95% confidence.

Border Cave, South Africa. Deposits at Border Cave spanning the MSA and Later Stone Age (LSA) yielded four ancient hominid specimens (Grün et al., 1990a). The stratigraphic sequence consists of an alternating series of brown sands (BS) and white ashes (WA) labeled with 1BS as the youngest. The hominid remains BC1 and BC2 are of uncertain provenance, but they have been linked to either layer 4BS or layer 5BS on the basis of adhering sediment; BC3 is an infant from a grave cut into 4BS that may have been dug during the deposition of the subsequent layer 1RGBS; BC5 has a secure provenance of layer 3WA (Grün and Beaumont, 2001). All are morphologically modern (Stringer, 2002).

The sequence has been dated by unpublished luminescence dates by Joan Huxtable (Grün and Beaumont, 2001), amino-acid racemization dates on ostrich eggshells published only as averages for each layer (Miller et al., 1999), a few bulk-charcoal conventional radiocarbon dates

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(Grün and Beaumont, 2001), a series of AMS radiocarbon dates (Bird et al., 2003) for the upper part, and a series of 71 ESR determinations (Grün and Beaumont, 2001). The ESR dates were analyzed by Millard (2006a) using stratigraphic constraints and the same approach as in this paper. Two of the ESR dates were identified as outliers by Grün and Beaumont (2001), but their exclusion from the data set made negligible difference to the results of the calculations. Table 3 compares the results of Millard (2006a) with those of Grün and Beaumont (2001), showing that the revised chronology is slightly shorter for the deeper strata.

Die Kelders, South Africa. Twenty-seven human remains have been recovered from several sets of excavations at Die Kelders Caves 1 and 2, constituting at least 10 individuals (Grine, 2000). They are mostly isolated teeth with two manual phalanges and a fragment of mandible. Their morphology is neither distinctively modern nor archaic (Grine, 2000). Eighteen of the specimens, including the phalanges and mandibular fragment, derive from Layer 6, whereas the others are scattered through Layers 4/5 (youngest), 8, 10, 11, 14, and 15 (oldest). Electron-spin-resonance dates have been obtained from layers 4/5, 6, 10, and 12 (Schwarcz and Rink, 2000) and from Layers 4/5, 7, 9, 11, and 13 by luminescence (Feathers and Bush, 2000). Early-uptake ESR and luminescence dates are in agreement, placing the deposits in the range of 70 ± 4 and 70–60 ka, respectively. Thackeray (2002) presented an alternative analysis using principal components analysis of micromammal-species abundance to derive a temperature index that he compared to the marine oxygen-isotope record. However, Thackeray's analysis does not allow for any uncertainty in the reconstructed temperatures, so although his correlation of the sequence with a much younger date range spanning oxygen-isotope stage (OIS) 3 (i.e., 60–20 ka) may be possible, it is impossible to tell if alternative ages are also compatible with this analysis.

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The luminescence and ESR dates were reanalyzed for this study incorporating stratigraphic information and important correlations between the results of the techniques due to the large uncertainty in water content of the sediments. Feathers and Bush (2000) calculated alternative dates using 10%, 15%, and 20% water content with an uncertainty of ±5%. Schwarcz and Rink (2000) calculated alternative dates assuming 10%, 20%, and 30% water content. It seems prudent to allow for this uncertainty by assuming a water content of 20 ± 10%. Feathers and Bush (2000) conducted a detailed study of luminescence using TL, OSL, and IRSL, which were all in agreement. The TL and OSL methods differ in the determination of the equivalent dose but have exactly the same dose rates for a given sample, so the equivalent doses were combined. Infra-red stimulated luminescence is measured on feldspars and, as no checks for anomalous fading were conducted, the two IRSL samples were excluded from this analysis on the grounds of chronometric hygiene, although it should be noted that they agree within their uncertainty with OSL dates on the same strata. The small cosmic-dose component was calculated differently in the original papers. For luminescence, 5.5 m of rock above the cave was assumed, while for ESR, 24 m of overburden was assumed. Examination of the photographs of Marean et al. (2000) shows that 5.5 m is likely to be the correct value, so the values given by Feathers and Bush (2000) were used for this study instead of the values of Schwarcz and Rink (2000). Two of the ESR samples were conjoining pieces of a tooth found in layers 4/5 and 6, so these layers have to be regarded as one stratigraphic unit for dating purposes.

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On the basis of a Bayesian stratigraphic model incorporating the luminescence dates and EU ESR dates, the hominids in layers 4/5 and 6 can be placed at 72–48 ka, while those from layers 8, 10, and 11 are 79–66 ka, 83–72 ka, and 85–73 ka, respectively. The hominids from layer 14 are older than the oldest luminescence date in layer 13 and so are older than 78 ka.

Older dates would be obtained by calculation using the luminescence dates with LU ESR dates, but the two sets of dates are inconsistent with each other. These dates cover a wider range than the 70–60 ka and 70 ± 4 ka quoted in the original dating papers, as well as the assignment of 74–59 ka (OIS 4) derived from sedimentological considerations (Grine, 2000). While it is possible that the deposits accumulated over a short time interval, as assumed by Grine (2000), a longer time span is also possible.

Equus Cave, South Africa. Equus Cave has yielded 10 human teeth of Pleistocene age and one mandibular fragment, probably from Pleistocene levels (Grine and Klein, 1985). The cave was formed in the Oxland Tufa, the youngest parts of which are dated to 230 ± 17 ka by uranium-thorium (Vogel and Partridge, 1984). Butzer et al. (1978) stated that the sediments are older than a widespread manganiferous patina. This patina is older than the Blue Pool Tufa II, which has a minimum radiocarbon date of 15,980 ± 230 BP, and younger than the Blue Pool Tufa I, which has uranium-thorium ages ranging from 30 ± 3 to 103 ± 6 ka (Vogel and Partridge, 1984). The patina is also younger than a travertine at Witkrans Cave dated by radiocarbon to a minimum of 33,150 ± 2,500 BP (Berger and Libby, 1966; Clark, 1971). Butzer et al. (1978) argued that the dissolution of Equus Cave was contemporary with the formation of the Blue Pool Tufa I. The human remains are thus broadly constrained between a calibrated radiocarbon age of 17,600–16,850 BC and the formation of the Oxland Tufa at 230 ± 17 ka and most likely belong to the period between 103 ± 6 ka and 30 ± 3 ka. Given the weak stratigraphic correlations, a more sophisticated analysis is not warranted.

Florisbad, South Africa. Parts of a cranium and a maxilla were recovered from the Florisbad spring deposits in 1932 (Grün et al., 1996). The only dating, by ESR and OSL, was reported by Grün et al. (1996). No details of the chronometric measurements were given, with

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most ages shown only on a diagram and a few central ages and uncertainties given in the text. There is a stratigraphic sequence of dates by both methods, but the reliability of the ESR dates must be considered uncertain, as Figure 1a of Grün et al. (1996) shows that they decrease with increasing depth. An ESR date on a fragment of the hominid tooth gave a date of 259 ± 35 ka, while the OSL date on the peat in which it was found was 281 ± 73 ka (Grün et al., 1996; Bamford and Henderson, 2003). The best available estimate for the age of the hominid remains is the 95% confidence range of the direct ESR date, 329–189 ka.

Hoedje's Punt, South Africa. The dating of the layer that contains human teeth and other remains is unclear due to underreporting of chronometric data. The initial report on the site (before hominid remains were found) by Volman (1978) assigned a broad age based on finds of MSA artifacts. Berger and Parkington (1995) discussed the site in more detail and suggested that the foraminiferal assemblage in the hominid-bearing layers indicated a marine regression prior to the OIS 5 to 4 transition, (i.e., prior to 78 ka). However, a calcrete capping the whole stratigraphic sequence is said to yield a U-series age of about 300 ka, with no further details given (Berger and Parkington, 1995). Neither these authors nor subsequent ones have discussed how such an old age is possible for a capping deposit, given the other data. More recently, Stynder et al. (2001) quoted unpublished luminescence ages that placed the overlying DAMA layer at ca. 117 ka and the hominid-bearing HOMS layer at younger than 550 ka. Citing faunal correlations to the Florisbad Faunal Span and the ESR date on the Florisbad hominid (Grün et al., 1996), Stynder et al. (2001) suggested "a maximum age around 250 ka" (p.372) but then stated that the hominid bearing sands were "most probably deposited between 200 ka and 300 ka ago" (p.372). . Klein (1999: 399) assigned an age of 300–71 ka based on "U-series, geologic context, associated fauna." Given these pieces of evidence, it seems that the age of the remains

Comment [MSU37]: Page numbers for quote must lie between the luminescence ages (though without uncertainty estimates this is not a particularly useful statement) and be within the floruit of the Florisbad fauna, which itself can only be stated to include the 259 ± 35 ka date of the Florisbad hominid.

Kabwe (Broken Hill), Zambia. The remains of "Rhodesian Man," along with faunal remains, were discovered in 1921 by miners (Klein, 1973). The principal dating is based on Klein's (1973) assessment that the fauna is similar to that at Elandsfontein and broadly similar to those from Olduvai Gorge Upper Bed II through to Bed IV. There are no chronometric determinations. On the basis of the faunal correlation to Olduvai (Figure 1), an age of younger than 1780 ka and, depending on the chronology for Olduvai, either older than 990 ka (on the long chronology) or, more likely, older than 490 ka (on the short chronology) may be assigned (see under Olduvai above). This is consistent with Elandsfontein being older than 330 ± 6 ka (Table 1).

Klasies River Mouth, South Africa. Klasies River Mouth (or Klasies River Main Site—KRM) has a yielded a long sequence of stone tools and fossil hominids (Singer and Wymer, 1982). It serves as a reference sequence for many aspects of the MSA in southern Africa. The deposits are divided into a series of members (Figure 2), starting with the Lower Brown Sands (LBS), followed by the Sand-Ash-Sand (SAS), Rockfall (RF), White Sands (WS), and Upper members, with the Upper Member divided into the Howieson's Poort (HP) and Middle Stone Age 3 (MSA3) (Singer and Wymer, 1982). Hominid fossils have been found in numerous layers within all members but RF, but the majority come from the lower part of the SAS Member (Singer and Wymer, 1982). The morphological status of the fossils has been summarized by Grine et al. (1998: 106) as "suggesting a pattern of overall, albeit incomplete morphological modernity. The cranial and especially the postcranial bones from KRM present a

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mixture of primitive and modern features." A number of dating attempts have been made and reported in varying detail. Amino-acid-racemization ages have been published in summary form (Brooks et al., 1993; Miller et al., 1999), whereas luminescence dates have been published in full (Feathers, 2002), as have ESR dates (Grün et al., 1990a) and U-series dates on speleothems (Vogel, 2001).

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Two of the dates reported for KRM were rejected on chronometric-hygiene grounds. The ESR sample 547 was "found on the floor and thought to be derived from the nearby wall" (Grün et al., 1990a: 429), and therefore does not have a secure stratigraphic provenance. The TL and OSL measurements of the burial dose for luminescence sample UW227 differ significantly, though they should be the same, and this sample was therefore rejected as unreliable.

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For calculation of the chronology, the estimates of water content with the most conservative errors are those of Feathers (2002) of 20 ± 10% throughout, except 6 ± 3% in the WS Member. The variable cosmic dose rates through the site as estimated by Feathers were used. For the U-series dates at KRM, a correction for initial ^{230}Th had to be made. Following Vogel (2001), the reasonable but arbitrarily chosen value of unity was taken for the initial ^{230}Th/^{232}Th ratio.

Klasies River Mouth has one of the more complex stratigraphic orderings considered in this paper (Figure 2), with the RF and WS members both overlying the SAS Member but not able to be ordered stratigraphically. In addition, a stalagmite from the SAS member has internal ordering of multiple U-series dates from the base to the top. All of these orderings are included in the calculations. Some strata do not have temporal constraints on both their start and end, and a terminus ante quem or terminus post quem for the stratum was calculated.

Analysis of the luminescence, U-series, and ESR dates yields dates for hominids from the various units as shown in Table 4. The differences between the chronologies in the lower strata are small compared with the ages and make little difference to their interpretation in terms of human evolution, but in the higher strata, the differences are a significant proportion of the ages. The revised ages are broadly compatible with the previous estimates by Deacon (1989), but suggest a wider range of dates for the SAS Member. The Howieson's Poort industry is shown to be later than Deacon's estimate, with the modeled start of the industry in the interval 65–49 ka (EU) or 63–51 ka (LU). This is somewhat later than the 82–68 ka date for the start of the Howieson's Poort at Border Cave (Millard, 2006a). The morphologically modern fossils from the lower SAS Member are most likely earlier in the possible range for that member, but without a significant number of additional dates, it is not possible to know the date more precisely. There is clearly scope for additional ESR and OSL dating, targeted specifically at the SAS Member, and it would be worth revisiting the U-series dating using modern high-precision mass-spectrometric techniques.

Mumbwa, Zambia. A series of teeth and long-bone fragments have been recovered from middle and late Pleistocene levels at Mumbwa (Pearson et al., 2000). The sequence is dated by TL dates on sediments and one OSL date. Electron-spin-resonance dating has been carried out, but no details were reported by Barham and Debenham (2000). The sequence of dates conforms to the stratigraphy, except that the two dates from lowest in the stratigraphy, separated by 3 m of sediment, are virtually identical at 172 ± 22 ka (Unit XIV) and 172 ± 21 ka (Unit IX). Barham and Debenham (2000) rejected the age on the lowest sample as too young, citing the micromammal evidence of Avery (2000), and placed Unit XIV (the bottom of the sequence) at around 255 ka. Avery's (2000) reconstruction of climate from the micromammals suggested a series of climatic fluctuations in the lowest 3 m, which were correlated to marine isotope stages using the chronology of Barham and Debenham (2000). Given the circularity of these arguments, there appears to be no strong argument for rejecting the TL date from Unit XIV, and there is no indication of any technical problem, such as saturation of the TL signal or incomplete bleaching. Given the uncertainties of the dates, a simple analysis of the possible difference between these dates suggests that it is 60–0 ka at 95% confidence. Avery assigned each stratigraphic unit of the site to a separate isotope stage or substage, but it seems quite possible that some of the variations are within-OIS variations, and that there was a rapid accumulation of sediment.

Insufficient detail of the luminescence-dating measurements is given for a full analysis following the methods of Millard (2006b), so the sequence was analyzed for this study by treating the dates as calendar dates in OxCal. This model puts the radial fragments from Unit XII at 220–149 ka, the two tooth fragments from Unit X at 204–138 ka, and the lower second molar and femoral fragment from Unit VII at 148–74.8 ka.

Sea Harvest, Saldhana Bay, South Africa. The only chronometric determination from this site is an infinite radiocarbon date of >40 ka from a shell midden stratigraphically above the horizon which contains a human manual phalanx and a premolar (Grine and Klein, 1993). Grine and Klein (1993) placed this material younger than 128 ka, as it is stratigraphically higher than a wave-cut platform of the last interglacial. On the basis of the fauna, they suggested that a last glacial age of 128–74 ka is most likely.

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Levantine sites

Amud, Israel. Remains of 18 individuals have been discovered, 15 from Middle Paleolithic contexts, and all from layers B_1 and B_2, except one from the earlier layer B_4(Valladas et al., 1999). Three skeletons are Neandertal in morphology—Amud I from layer B_1 and Amud II and Amud 7 (an infant) from layer B_2 (Valladas et al., 1999). The ESR dates on teeth (Rink et al., 2001) and TL dates on burnt flints (Valladas et al., 1999) have been obtained from the three relevant layers. The latter papers contain inconsistencies in the chronometric data. Valladas et al. (1999) gave uncertainties on the internal and external doses and uncertainties on their dates that are consistent with one another, but the overall dose rates received by the flints have uncertainties that are much greater than implied by the other data. The reported uncertainties on the overall dose rates were assumed to be incorrect and the consistent part of the data was used here. Flints from Squares O14 and O15 were excluded due to disturbances that are likely to have altered the external radiation dose. Examination of the values in the tables of Rink et al. (2001) and reproduction of their calculations show that all samples were dated using in situ measurements by gamma-spectrometry or TL dosimetry and none of the gamma dose rates used were calculated from sediment compositions, despite what is stated in the text. The in situ measurements were also used here. Following Rink et al. (2001), they were assumed to represent radiation dose with a water content of 10% and an uncertainty of 10%. Using the US-ESR uptake model, Rink et al. (2001) computed ages that fall midway between the EU and LU ages, which themselves only differ by a few thousand years. Table 5 shows the results of the Bayesian stratigraphic models for Amud. In comparison to the summary of Valladas et al. (1999), the new chronology is less certain, but in comparison to the averages presented by Rink et al. (2001), the 95% probability intervals are more precise than their 1σ ranges. The age for layer B_1, which contained the Amud I Neandertal, suggests that it is similar in age to the Kebara Neandertal or slightly younger.

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Dederiyeh, Syria. Remains of fifteen Neandertal individuals have been recovered from Middle Paleolithic contexts at this site, including two burials (Akazawa et al., 2004), but the site has not yet been systematically dated. Akazawa et al. (2004) reported that there are six preliminary radiocarbon dates ranging from 48,100 ± 1200 to 53,600 ± 1800 BP for layers 2–3, which are high in the stratigraphic sequence.

Kebara Cave, Israel. Various excavations have yielded 29 separate hominid finds associated with the Mousterian levels in this cave(Bar-Yosef et al., 1992). The most important is the well-preserved burial of an adult male Neandertal from Bed XII (Bar-Yosef et al., 1992). Thermoluminescence dates on flint have been obtained for Beds VI (youngest) to XII (oldest) by Valladas et al. (1987), but were only reported as mean dates for each layer. Schwarcz et al. (1989) obtained ESR dates for Bed X, the bed that they presumed "corresponds most closely to the 'living floor' at the time of burial." (Schwarcz et al., 1989: 654) Using the full data on the TL dating (Valladas, pers. comm.) and the ESR data, it makes little difference whether EU or LU ESR dates are used, because of the small difference between them in this site and the dominant effect of 37 TL dates. Two dates were omitted from the calculations: the TL date on flint N21,109 because the reported α- and β-dose rates are inconsistent with the reported radioelement concentrations, and the ESR date on tooth fragment H17cmoust, as the reported zero β-dose rate from the sediment seems to be an error. Most of the human remains catalogued by Bar-Yosef et al. (1992) come from layers IX, X, and XII, and the computed dates for these layers are shown in Table 6. The revised chronology is more precise for layers IX and X than the previous chronology based on simple averaging of TL dates but is essentially unbounded for layer XII, as there are no dates below this level.

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Qafzeh, Israel. This site has yielded five anatomically modern human burials, with fragments of up to 11 other individuals (Vandermeersch, 1981). The hominid remains come from layers XV (youngest) and XVII (oldest) of Vandermeersch and co-workers, excavated from 1965 to 1979, and layers F and L of Neuville, excavated from 1932 to 1935 (Vandermeersch, 1981). Layer F is not correlated with those of Vandermeersch and co-workers, from which the chronometric samples came, but layer L corresponds to layers XVII–XIX (Vandermeersch, 1981). Valladas et al. (1988) obtained TL dates on flint from layers XVII–XXIII, while Schwarcz et al. (1988) obtained ESR dates on odd-numbered layers from XV to XXI. Unfortunately, the ESR dates were reported without any chronometric data, and even without uncertainties, so that all that is available is a set of point estimates for one or two teeth per layer, and it is not possible to reanalyze these data.

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On the basis of a Bayesian stratigraphic model incorporating the TL dates, hominids Q8–Q12 and Q14–Q17 from layer XVII date to 95.2–87.0 ka. Specimens Q13 and Q18 from layer XV are not directly dated by the TL ages, but on the limited evidence of the ESR ages, they are unlikely to be much younger than the others. The stratigraphic positions of Q3 and Q6 are less well known, so they date to 96.9–87.6 ka. These dates are more precise than the 92 ± 5 ka average of TL dates for layers XVII–XXIII of Valladas et al. (1988) and reinforce their suggestion that the whole hominid assemblage accumulated rapidly.

Shanidar, Iraq. Nine Neandertal skeletons were excavated at Shanidar by R. Solecki in the 1950s. They were all found in the upper half of Layer D, which contained Mousterian tools, and was sealed by the Upper Paleolithic Layer C (Trinkaus, 1983). Two radiocarbon dates from the top of Layer D of 46,900 ± 1500 BP (GrN-2527) and 50,600 ± 3000 BP (GrN-1495) (Vogel and Waterbolk, 1963) and the correlation of a pollen-based climate sequence led Solecki (1963) to place the middle of Layer D at about 70–60 ka. Radiocarbon dates obtained so long ago and of such great age are likely to be minimum ages. No other more direct dating evidence is available for these fossils, so the best evaluation of their age is that they are over 50 kyr old by an indeterminate amount. A stalagmitic crust within Layer D predates all of the Neandertal remains, and, if still accessible, offers the opportunity for U-series dating, which might elucidate the date of this important hominid sample.

Skhul, Israel. Excavations by Dorothy Garrod recovered remains of 10 modern human individuals from burials in Layer B at Skhul (Grün et al., 2005). Layer B was divided into two parts distinguished by their hardness, with Layer B1 overlying Layer B2 (Grün et al., 2005). Thermoluminescence dates have been obtained on six burnt flints (Mercier et al., 1993), which were subsequently shown to have derived from Layer B2 (Grün et al., 2005). Electron-spin-resonance dates and U-series dates were obtained on 11 animal teeth and the hominid remains Skhul II and Skhul IX (Stringer et al., 1989; Grün et al., 2005). The stratigraphic position of the human and animal remains is known to be Layer B, but whether they came from B1 or B2 is unclear (Grün et al., 2005). The descriptions of Skhul II suggest that it may have come from Layer B1, and the depths of Skhul IX and Skhul V strongly suggest that they derive from Layer B2 (Grün et al., 2005). Two of the animal teeth were found in direct association with these human burials (Grün et al., 2005).

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Schwarcz et al. (1980) reported U-series ages on travertines from the alcove in which Skhul III was discovered. Unfortunately, the extent of removal of sediments makes stratigraphic correlation of these samples with the hominid and other remains impossible, and the dates of 79 ± 4 ka on one sample and >350 ka on three others cannot be used to estimate the dates of the human burials.

The three ESR and TL dating studies have taken different approaches to calculating the external dose rate of their samples, although in principle, the same γ- and cosmic-radiation sources were irradiating all of the samples. Stringer et al. (1989) computed a 380 μGya^{-1} γ-dose rate from dry sediment using chemical analysis of sediment attached to teeth and other archived sediment samples. They assumed a cosmic dose rate of 120 μGya^{-1} on the basis of less than 2 m of overburden and a water content of 10 ± 10%. Mercier et al. (1993) used this γ-dose rate estimate, but assumed a water content of 15% "on the basis of palaeoclimatic data" (Mercier et al., 1993: 173) (which was not specified), and a cosmic dose rate of 100 μGya^{-1} taking into account the geometry of the adjacent cliff. They assumed ±30% uncertainty on the external dose to allow for inhomogeneous chemical composition and variations in water content. Translated entirely into an uncertainty in water content, this would be equivalent to assuming a water content of 15 ± 31%. Grün et al. (2005) reevaluated the external doses. They analyzed a much larger suite of sediment samples and examined what is known about the stratigraphic position of their samples. To allow for sediment inhomogeneity, they calculated dose rates by weighting the dose rate from sediment attached to the tooth at 25% and that from the bulk sediment at 75% (as 25% of the γ-dose comes from sediment within 5 cm of the sample). They also noted that two samples (1057 and 1058) from close to the bedrock may have received lower dose rates. Their water content estimate is 10 ± 5%.

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For the purposes of integrating all dating evidence here, common assumptions for all the techniques were required. Water content was taken as 10 ± 10%, the most conservative of the published values. Sediment γ-dose rates for ESR samples were weighted following Grün et al. (2005). The uncertainty in the contribution to this dose rate from the wider sediment, and for the entire dose rate for the burnt flints, was computed by assuming that the sediment U, Th, and K concentrations are lognormally distributed with the same means and standard deviations as the set of sediment samples reported by Grün et al. This assumption is based on the facts that trace-element distributions are well approximated by a lognormal distribution (Aitchison, 1986) and that lognormal distributions give a better fit to Grün et al.'s (2005) compositional data than normal distributions. This assumption also has an advantage over the unwritten standard assumption of normal distributions, in that negative concentrations (and dose rates) cannot occur in the calculations. The cosmic dose rate of 116 ± 17 μGya^{-1} of Grün et al. is the most carefully considered estimate and was used here. In cases where bedrock contributed to the γ-dose rate, Grün et al. (2005) took its infinite matrix dose rate as 90 μGya^{-1} without uncertainty. As this was based on an in situ γ-spectrometer measurement, an uncertainty of ±9 μGya^{-1} was assumed here on the basis of a typical γ-spectrometer uncertainty of 10%.

Grün et al. (2005) reported combined U-series-ESR analyses of six samples, which ought to give more reliable ages because the assumptions of EU or LU can be relaxed. Unfortunately, there is currently no mechanism for fully including such dates in a Bayesian analysis. The US-ESR model and the CSUS-ESR model yield similar dates, and those dates are very close to the LU dates, so the best Bayesian computations that can currently be made are with LU dates and probably yield results close to the true values.

Computing on this basis leads to the dates given in Table 7. Direct association with ESR samples leads to more precise dates for Skhul IX and Skhul V than for the other hominids, which do not have directly associated dating samples. Although the Skhul hominids have been widely considered to date to 100–90 ka, the results here show a great uncertainty in their true age. These results contradict several of the conclusions of Grün et al. (2005): Skhul V appears quite likely to be younger than Skhul IX, the estimate for the date of Skhul V is somewhat younger than Grün et al.'s estimate, and the possibility remains that some or all of the hominids other than Skhul V and IX are late Middle Paleolithic or Upper Paleolithic in age.

Tabun, Israel. Tabun has one of the deepest and longest hominid- and artifact-bearing stratigraphies in the Levant and has served as a reference sequence for the region. Preservation of skeletal material is variable in the deposits, and correlation of the strata reported by excavations over a period of more than 60 years is not straightforward. Initial excavations in the 1930s divided the sequence into Layers A (youngest) to F (oldest), separate from the sequence in Chimney II (Garrod and Bate, 1937).

Hominid remains were recovered in the 1930s excavations by Garrod and Bate (1937). They were numbered B1, B3, B4, and B5 from Layer B, C1 to C7 from Layer C, E1 from Layer Ea, and E2 from Layer Eb. Specimens BC2 and BC6 were recovered from Chimney II. Specimens C1 and C2 are also known as Tabun I and Tabun II. Most authors consider all of these specimens to be Neandertal in form (Oakley et al., 1977). Bar Yosef and Callander (1999) reviewed the evidence for the stratigraphic position of C1 and suggested that there is a possibility that it originates from Layer B. Coppa et al. (2005) reviewed all the dental material from Tabun and suggested that there is a new individual, BC7, from Layer B, although they identified the teeth with those that Garrod and Bate (1937) reported as recovered from the outermost fringe of Layer C. Electron-spin-resonance measurements show that the radiation dose received by the teeth is consistent with doses of animal teeth in Layer B and not with those from Layer C (Coppa et al., 2005). Coppa et al. (2005) disagreed with some previous tooth identifications, but apart from suggesting that BC2 and B5 represent the same individual, they did not suggest any other revised stratigraphic assignments.

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Animal tooth enamel from the archive of Garrod's excavation has been dated using ESR (Grün et al., 1991; Grün and Stringer, 2000), with external dose rates estimated from sediment samples attached to the teeth or otherwise in the archive. Subsequent excavations directed by Jelinek (1982) and Ronen (Ronen and Tsatskin, 1995) have also recovered datable material. Jelinek and Ronen provided more detailed stratigraphic sequences, but these are not always directly correlated with the larger units used by Garrod. A sequence of TL dates on burnt flint derive mostly from flints recovered by Jelinek (Mercier et al., 1995, 2000; Mercier and Valladas, 2003) from strata correlated with Garrod's Layer C and below. Rink et al. (2004) obtained ESR dates for a single tooth recovered in Ronen's excavation from layers equivalent to Garrod's Layer Ed.

Uranium-series dating was carried out on animal teeth by McDermott et al. (1993) and on the bones of hominid C1 by Schwarcz et al. (1998). The difficulty of knowing the uranium-uptake history renders these dates problematic, but while those obtained from teeth can be used to constrain the uptake model used for the ESR dates, Millard and Pike (1999) showed that the measurements made on the bones of Tabun C1 are of little use for dating.

The TL dates of Mercier et al. (1995, 2000) and the ESR dates of Grün et al. (1991) have been the subject of debate, as they disagree in the lower levels of the site. Mercier et al. (1995) suggested that the elemental concentrations in the sediments used by Grün et al. (1991) had been altered postdepositionally, thus shortening the ESR chronology. Grün and Stringer (2000) showed that the differences persist with a larger suite of sediment samples from the Garrod collection, and their analyses are therefore likely to be representative of the sediments from which the teeth came. A further problem is the poor correlation of Jelinek's stratigraphy with Garrod's sequence. Farrand (1994) discussed the fact that Garrod's layers were not natural stratigraphic units, being at least partially based on stone-tool typology, and the reality of the stratigraphy is much more complex than might appear from the small number of labeled layers. Garrod excavated the entire contents of the outer chamber of the cave, so "there is no way of relating Garrod's finds to Jelinek's stratigraphy in detail" (Farrand, 1994: 34), and doubts must always remain about the relationship between the two stratigraphic sequences and the position of the hominids within them. At best, the hominid remains can be assigned to Garrod's layers, but the possibility remains that hominid C1 actually derives from Garrod's Layer B (Bar-Yosef and Callander, 1999).

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As the latest revision of the TL chronology (Mercier and Valladas, 2003) updates both the internal dose rates and the equivalent doses, but does not give detailed data for either, and it is impossible to calculate the appropriate figures from the published data, the TL dates cannot be treated fully using the methods of Millard (2006b). Consequently the chronologies presented below used the TL dates as independent estimates of calendar dates, ignoring any correlation of uncertainty between them. The resulting chronologies are likely to have somewhat underestimated uncertainties.

As a consequence of the problems outlined above, several models were used to calculate five alternative chronologies, shown in Table 8: TL only, EU-ESR only, LU-ESR only, TL with EU ESR, and TL with LU ESR. Of these, the last two are not internally coherent due to the differences between results from the two techniques, and are dependent on the assumption that the correlation of Jelinek's and Garrod's stratigraphies is correct. These combined TL-ESR chronologies are presented for comparative purposes only.

From the data of McDermott et al. (1993), U-series dates using EU or LU can be calculated and compared to ESR dates calculated on the same basis, in order to help resolve whether EU or LU dates are more reliable. The comparison shows that all U-series dates fall within error of the published ESR dates, except for LU dates from Layers D and Ea, but the uncertainties of the ESR dates are so large as to render the comparison largely meaningless. Comparison of the U-series ages with the dates from the Bayesian stratigraphic models (Table 8) shows that EU U-series dates mostly fall short of the date for the relevant stratum from the TL-only chronology and short of the posterior date for the same sample in the two EU-ESR chronologies. In contrast, LU U-series dates are generally older than the TL-only and the two LU-ESR chronologies. Overall, when the dates computed here are compared to the relatively precise U-series dates, no more than two of the six U-series dates match with the dates of appropriate samples or layers in the modeled chronology, but the EU dates for U-series and ESR are less discrepant than the LU dates. The U-series determinations are not useful in forming a chronology themselves, but they do indicate that, all else being equal, the true chronology should be shorter than the LU-ESR chronology and closer to but longer than the EU-ESR chronology.

These chronologies are mostly more precise than the comparable published chronologies. Expressed as 95% probability ranges, they make it clear that all hominids from Tabun are imprecisely dated, but especially those from Layer B and, on the TL chronology, Layer C. The revised chronologies are slightly younger than the previously published ones, but not sufficiently different to change the broad placement of the fossils. The TL and EU-ESR chronologies show a measure of agreement on the date of Layer C, but still differ in Layers Ea and Eb.

The conundrum of which chronology—TL or ESR—best dates the Tabun hominids remains. The ESR dates are better associated stratigraphically with the hominid remains, but doubts remain over the reliability of that stratigraphy, the sediment dose rates, and the uptake model to use, while the TL dates have a more secure stratigraphic sequence and more certain external dose rates, but even weaker correlation with the hominid fossils' stratigraphic positions. The TL-only and EU-ESR-only chronologies represent the two best alternatives, though that based on EU-ESR will be shorter than the best possible ESR chronology, and the uncertainties in the one based on TL are underestimated. To resolve the chronology of this important site will require further dating, with samples carefully chosen to avoid as many of the problems with reliability as possible that have limited this analysis.

Zuttiyeh, Israel. The Zuttiyeh partial cranium was excavated in the 1920s, and its stratigraphic position within the cave was poorly recorded (Schwarcz et al., 1980). It appears to come from below the artifact-bearing layers, which yielded Acheulo-Yabrudian tools. The only chronometric dating that has been performed is U-series on travertines—Schwarcz et al. (1980) reported an age of 164 ± 21 ka for a sample that they considered to be coeval with or postdating the skull. Other dates on Acheulo-Yabrudian assemblages suggest that it may well be as old as 400–200 ka (Barkai et al., 2003). If Schwarcz et al. (1980) correctly interpreted the stratigraphy, then the skull must be older than 122 ka.

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Discussion

From the compilation and consideration of the chronometric evidence for African and Near Eastern hominids, a series of issues and problems relating to chronological data can be identified, and the revised chronology has implications for various aspects of our understanding of human evolution.

Problems with chronological data

Stratigraphic hygiene. In some cases, doubts about the stratigraphic provenance of a fossil are recorded in the literature (e.g. for BC1 and BC2 from Border Cave; Grün and Beaumont, 2001), but the stratigraphic positions are frequently stated as if they are confidently known. For many fossils this confidence is warranted, but doubts may have been forgotten, as happened with Tabun B1 (Bar-Yosef and Callander, 1999). With the more recent remains, there is the particular problem in which graves cut into lower levels but are not recognized as such during excavation, as demonstrated by the direct dating to the Neolithic of the supposedly Aurignacian human remains from Vogelherd (Conard et al., 2004). Direct dating of hominids is more difficult beyond the range of radiocarbon, and thus this will always be a problem for earlier remains. Uncertainties about the stratigraphic provenance of some hominid fossils are inevitable, and even though the deliberate selection of dating samples that lack stratigraphic relationships with the hominids, fauna, or archaeology of interest is avoidable, it has happened (e.g., at KRM [ESR sample 547] and Skhul [U-series dating]).

Lack of datable materials. Despite the large number of chronometric determinations reviewed here, some fossils are still only dated by faunal correlations or to broad time periods between dated stratigraphic horizons. In some cases the lack of precision in our knowledge of their dates extends to hundreds of millennia, so that they cannot be chronologically ordered with other fossils with full confidence. In some cases, this may be the best that can be done, as no new evidence can be adduced (e.g., the Berg Aukas femur); however, it is clear that, if some key specimens (e.g., Kabwe) are to be securely placed and used to infer evolutionary sequences, then improved dating techniques are required.

Technical aspects of chronometric hygiene. For significant proportion of sites considered in detail above, inadequate reporting of the details of the chronometric data that support the dates presented is a problem. No examples of full reporting of amino-acid-racemization data were found. Of the 34 sites examined, six had luminescence dates reported at a level of detail inadequate for reevaluation, as did three for ESR, two for U-series, and one for Ar-Ar. Authors need to publish the detailed data, or make it available on request, especially as (1) calculation of dates depends on constants such as half-lives that have been revised over the years, and (2) three of the papers that did give full data contained errors in the calculations or performed them differently from their stated method. For the trapped-charge techniques (ESR, OSL, TL), different authors were occasionally inconsistent in their calculations of dose rate from the same sediment, which can be excused due to the passage of time between the application of the different techniques, but cannot be excused when it occurs in consecutive papers in the same journal (i.e., Feathers and Bush, 2000; Schwarcz and Rink, 2000).

Dating of bones, teeth, and mollusc shells by ESR or U-series depends on an understanding of uranium uptake, and lack of understanding has clearly hampered the construction of reliable chronologies. This led to competing EU and LU chronologies at most sites dated by ESR, and there were four cases of U-series dating of bone and one of mollusc where these were presumably the only materials available, but the dates had to be rejected as unreliable. A better understanding of uranium-uptake processes, as has been achieved to a certain extent for bone (Millard and Hedges, 1996), would be an important advance in dating.

Laser-fusion argon-argon dating generates large numbers of dates on an individual sample, and the assessment of the consistency of those dates and the evaluation of the likely true date of the sample is a crucial part of the procedure. Previous methods of data reduction were critiqued above, and the method of Ward and Wilson (1978) advocated for determining the coherence of a set of dates. However, although the Ward and Wilson (1978) method is adequate to determine whether the dates are the same, it may not be the best method for identifying outliers. It would therefore be preferable if formal statistical methods for outlier detection could be developed based on an understanding of the physical processes involved.

Use of the literature. In conducting this review of the chronometric evidence for African and Near Eastern hominids, the search for the detailed chronometric data was hampered by overreliance of many authors on the secondary literature. It is not uncommon to find a date cited from a publication, which upon checking simply cites another publication, which cites another, which cites the paper that first suggested the date. Frequently in such a chain of citations, the justification for the original date is lost, and in some cases, error limits disappear. For example, the ESR date of 259 ± 35 ka for the Florisbad hominid (Grün et al., 1996) can be applied to the Florisbad fauna, but somehow in the discussion of Stynder et al. (2001), this becomes simply "a maximum age of around 250 ka" (p.372) for the Florisbad Faunal Span, and in McBrearty and Brooks (2000), it becomes a bald 260 ka age without any uncertainty for the Florisbad hominid itself. Sometimes, the primary proposal for a date is based solely on comparisons of morphology to the best-dated fossils at the time of publication, and for later papers to suggest evolutionary sequences based on this date is obviously problematic. Given the flux in dating methods, the fact that problems have often been identified some time after the introduction of these methods, and the changing understanding of the dates of faunal successions, every author should be beholden to check the basis of the dates cited and apply some basic chronometric hygiene.

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Implications of the revised hominid chronology

Table 9 and Figures 3 and 4 summarize the chronology for fossil hominids developed in this paper. Figure 3 shows that the geologically older specimens are relatively poorly dated, and those dates rely mainly on faunal correlations. In particular, where the relevant specimens have been considered here, there is imprecise dating of hominids assigned to Group 1 by McBrearty and Brooks (2000) or to *Homo ergaster* and early *H. sapiens* by Klein (1999: 265–266). A few are well dated, and their ordering is fairly clear (Kapthurin, Lainyamok, Florisbad, Tabun, Mumbwa), but of these, only Florisbad and Tabun are particularly diagnostic (Klein, 1999: 275).

The age estimated here for Kabwe differs significantly from that quoted by previous authors, and, with the date for Bodo, places the appearance of archaic *H. sapiens* before 490 ka. However this date is dependent on the two sites' faunal correlations with Olduvai, and it is therefore only semiquantitative and not entirely certain. A direct comparison of the Bodo and Kabwe faunal suites might help strengthen the dating. This early dating is similar to that of OH 23, which is usually assigned to *H. erectus* or *H. ergaster*, and therefore the relationship between these specimens should be reevaluated.

The geologically younger fossils (shown in Figure 4) tend to have more precise and better-defined ages, due in part to a number of more recent excavations focused on MSA sites and the availability of several alternative chronometric techniques (ESR, TL, U-series) applicable to sites dating to less than 250 ka. The dating of Omo by McDougall et al. (2005) changed the dates from those of previous compilations, and, with the remains from Herto, suggests a longer chronology for what are recognized as morphologically modern humans. Conversely, the dates deduced for Jebel Irhoud are younger than those used by the previous studies, but again rely on the fauna, though in this case the support of poorly reported ESR dates adds confidence to the faunal analysis. The Qafzeh hominids are closely dated and somewhat more recent than Stringer (2002) had placed them. In contrast, the remains from Skhul, which are considered to be very similar in morphology, are much less precisely dated and not necessarily contemporary with Qafzeh. With the Q3 and Q6 specimens date at 97–88 ka and Skhul IX dated at 173–106 ka, it is clear that Skhul IX is earlier than all of the Qafzeh hominids. The possibility should be considered that the two sites represent different populations, even perhaps separate incursions of African *H. sapiens* into the Levant during OIS 5c (Qafzeh) and OIS 5e (Skhul).

Comment [MSU60]: Date for reference

In general, the dates arrived at here are less certain than many of those presented in the literature, and consequently, the current chronological scheme is compatible with various hypotheses about the evolution of *H. sapiens*. The three previous studies summarized in Table 9 (and numerous others) have confidently ordered fossils, labeling them early or late and archaic or modern, but the dates presented appear to be selective, and sometimes towards one end of the possible range for a particular fossil. The construction of evolutionary sequences depends on the use of both morphology and dates, but given the uncertainty of the chronometric evidence, it seems that many of these evolutionary schemes order fossils on the basis of their morphology. Where we have well-dated fossils, some of the sequences conform to expectations based on judgments of the archaic or modern nature of their morphology but others do not. This is exemplified by the near closeness in date of Omo I and Omo II demonstrated by McDougall et al. (2005), in contradiction to many previous studies that concluded that these formerly poorly provenanced specimens were of widely different ages due to their different morphologies. Within the chronology developed, here it would be feasible that there was more morphological variability than is envisaged by most accounts of the evolution of *H. sapiens*. Whether this is so, or merely due to the chronological uncertainties, remains to be seen.

The issue of the sequence of modern human and Neandertal occupation of the Near East has been debated for many years. The chronometric evidence reviewed here shows that some of the remains can be put into temporal order with confidence, but that much ambiguity remains (Figure 4). It is clear that the Qafzeh modern humans are younger than Tabun C and Zuttiyeh, and that the Neandertals from Kebara and Amud B_1 are younger than Skhul V and IX and Qafzeh, as are the remains from Taramsa. The two species therefore did alternate in their occupation of the Levant, but the dating needs to be much more precise if a link between these occupations and climatic changes is to be proved or disproved.

Conclusions

Overall this study has found that, for hominid fossils from Africa and the Near East, the dating evidence for many key fossils is poor and that, in many cases, they cannot be ordered in time. The current chronology of the African and Near Eastern fossil hominids is unable to discriminate between the evolutionary schemes of the out-of-Africa hypothesis (Stringer, 2002), the multiregional hypothesis (Thorne and Wolpoff, 2003), and the hybridization-and-replacement hypothesis (Bräuer, 1989; Bräuer et al., 1997). Within this region these models differ only slightly in their ordering of fossils, but comparison with Asian (and to a lesser extent European) fossils is also necessary. The chronology of these fossils will be the subject of a future paper.

In order to put our understanding of human evolution over the last half million years on a firmer footing, further work in the dating and chronology of the fossils is required. Different sites will require different techniques, but a few promising methods need wider application, especially those applicable to materials excavated many years ago. Uranium-series dating of bone using the diffusion-adsorption model (Millard and Hedges, 1996; Pike et al., 2002; Pike et al., 2004) has proved its value in a few cases, and while it cannot be guaranteed to produce a date in every case, it should be used more often. Direct ESR dating of hominid fossils using small fragments of enamel has also reached a similar state of development (Grün et al., 2003; Grün et al., 2005). An advantage of these techniques is the direct dating of hominid material with a relatively small amount of destructive sampling. For sites with extant stratigraphy and documented positions of the hominid fossils, there are of course a wider range of techniques that can and should be applied—for example, dating of Klasies River Mouth has been improved by sampling for luminescence dates many years after the original excavations (Feathers, 2002).

Comment [MSU61]: References

An alternative, and perhaps more widely useful development, would be an improved chronology for the African faunal sequence and quantitative methodologies for comparison of faunal assemblages to derive dates. From the literature reviewed here, it is clear that a similar and larger-scale project could reevaluate the dates of faunal assemblages. In addition, there are methods for quantitatively correlating and dating faunal assemblages—for example, Alroy's (2000) dating of North American fauna or Weiss et al.'s (2003) analysis of trilobite faunas, which might be applied to African sites. Overall there is still much to be done to date the evidence for the last half million years of human evolution in Africa and the Near East.

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Table 1
Dating of sites without chronometric evidence

Site	Fossil(s)	Commentary
Ain Marouf, Morocco	Hominid femoral shaft	The associated fauna is comparable to that from Tighenif, but slightly more recent (Geraads et al., 1992); it is therefore younger than 780 ka.
Berg Aukas, Namibia	Hominid femur	Grine et al. (1995: 151) stated that it is “not possible … to place [the femur] in a geochronological context.” There is no associated fauna.
Cave of Hearths, South Africa	Hominid mandible from Bed 3 and radius fragment from the fill of a sinkhole	The dating of this site is poor and the literature is confused. Mason (1988) described it but gave very limited information on its dating. Beds 1–3 contained Acheulean materials, and he assigned them an age of 500–200 ka (p. 181), or 250–200 ka (Fig. 20C on p.47; see also p. 580), though no reasoning was given for either range of dates. He noted the mixed nature of the ESA and MSA materials in the sinkhole (p. 75) but considered that the radius was most likely contemporary with the mandible, given its morphology (p. 189). Pearson and Grine (1997) cautiously assigned the radius to either late ESA or MSA. Mason (1993) mentioned the mandible, suggesting a possible age of 250 ka in his abstract, but did not discuss dating in the body of the article. Bräuer et al. (1997) plotted a most likely age of 200 ka but did not indicate to which fossil it refers nor the source of the date.
Dar es-Soltane, Morocco	Two adult skeletons	Bräuer et al. (1997) plotted a “most likely” age of 90 ka for these skeletons, but cited no reference for this. Oakley et al. (1977) suggested a “final Soltanian” age, which would place the deposits in the late glacial, younger than 35 ka.
Elandsfontein (alias Hopefield, Saldanha), South Africa	Calvaria and part of a mandible	The remains were recovered from surface deposits. There are no chronometric determinations. Klein and Cruz-Uribe (1991) described the fauna as early mid-Quaternary and suggest a date of “perhaps” 700–400 ka by comparison to dated faunal sequences. Potts and Deino (1995) suggested a minimum age of 330 ± 6 ka by comparison with the Ar-Ar dated fauna at Lainyamok.
Eliye Springs, Kenya	Cranium	Although the cranium was found out of stratigraphic context in deposits reworked by wave action, Bräuer and Leakey (1986) considered that it probably came from deposits underlying the Holocene Galana Boi beds. They assigned a date of 200–100 ka based on cranial morphology. Bräuer et al. (1997) plotted a most likely age of 200 ka but gave no reference for this. Only a probable pre-Holocene date can be assigned.

Kabua, Kenya	Partial cranium and mandible	A partial cranium and mandible were found in surface collection in the Turkana District. They may derive from late Pleistocene lake sediments or from more recent burials intruded into those sediments. Rightmire (1975) considered that they were closer morphologically to modern *H. sapiens* than to the Kabwe skull. There is no real evidence to assign anything other than a broad possible date range of late Pleistocene or Holocene.
Wadi Dagadlé, Djibouti	Maxilla	This is broadly dated from the associated fauna to 900–100 ka (de Bonis et al., 1988).
Geulah Cave, Israel	Three fragmentary anatomically modern human bones	These were found in a Mousterian context in the cave (Arensburg, 2002). They are therefore older than 40 ka and younger than about 250 ka on comparison with the sequence at Tabun.
Nadouiyeh Aïn Askar, El Kowm, Syria	Parietal attributed to *H. erectus*	This was discovered in the complex deposits of a spring at this site and was hypothesized to be between 350 and 450 ka by correlation with the date of the Yabrudian at Tabun and the date of marine isotope stage 12 (Jagher et al., 1997). Subsequently, the parietal was stated to have been found in a late Acheulean context dated to 400–150 ka (Muhesen, 2001), but also to be about 450 ka in age (Le Tensorer et al., 2001). Only a vague middle Pleistocene age can be assigned.
Salé, Sidi Abderahman, and Thomas Quarries, Morocco	Various hominid remains	All three sites are late Amirian or early Tensiftian in age and likely contemporary with the Anfatian marine transgression(s) (Hublin, 1985). The Anfatian can be correlated with either oxygen-isotope stages 7, 9, and 11 (Hublin, 1985) or 9, 11, and 13 (Ward, 1985), so the age is uncertain but likely between 190 ka and 525 ka.
Tighenif (alias Ternifine), Algeria	Teeth, mandibles, and a parietal	The sediments are normally magnetized and the fauna are younger than several middle early Pleistocene sites and older than Thomas Quarries and therefore close in time to the early/middle Pleistocene boundary (Geraads et al., 1986). Hublin (1985) equated this to 1000–600 ka. However, the combination of fauna and normal magnetization supports Klein's (1999: 275) assignment of an age of slightly less than 780 ka.
Um el Tlel, Syria	Small fragment of an adult Neandertal	Muhesen (2004) remarked on the existence of these remains but gave no source. Boëda et al. (1999) mentioned preliminary TL dating of Mousterian levels, which had yielded "an age in excess of 50,000 years" (p. 394).

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Table 2
Dates of pumice clasts in the Kibish Formation

Member	Sample number	Number of LF-Ar-Ar measurements	Number of outliers removed		Weighted mean age (ka)	
			McDougall et al.	This study	McDougall et al.	This study
Member I						
	99-273A	9	0	2	315.3 ± 3.6	311.3 ± 3.2
	99-273B	8	1	1	210.9 ± 2.1	211.1 ± 1.8
	02-01B	15	1	3	191.5 ± 1.9	189.6 ± 1.4
	02-01A	16	0	3	205.3 ± 2.2	199.3 ± 2.0
	02-01C	14	0	2	192.7 ± 2.3	200.1 ± 2.5
Member III						
	99-275A	10	0	0	106.0 ± 1.6	106.0 ± 1.4
	99-275C	13	2	2	105.4 ± 1.8	108.2 ± 1.7
	99-274A	13	0	1	98.2 ± 1.1	99.8 ± 1.1
	99-274B	14	1	3	109.6 ± 1.3	105.2 ± 1.6

These dates are recalculated from the Supplementary Tables 2–4 of McDougall et al. (2005). A full listing of individual laser-fusion ages included and excluded is in the online supplementary information.

Table 3
Ages of Border Cave hominids

	Grün and Beaumont (2001) (ka)	Millard (2006a) (ka)
BC 1 and 2 if from 4BS	82	91–71
BC 1 and 2 if from 5BS	170	171–152
BC3	76	90–66
BC5	66	72–61

Table 4
Chronologies for Klasies

Unit	Date according to Deacon (1989) (ka)	Dates with EU ESR (this study) (ka)	Dates with LU ESR (this study) (ka)
MSA3		Younger than 48	Younger than 52
Howieson's Poort	~70	60–42	60–47
RF Member		71–52	71–54
White Sands (WS)	~ 60	Younger than 70	Younger than 71
Sand-Ash-Sand (SAS) Member	100–80	102–63	104–64
Lower Brown Sands (LBS)	Older than 100	Older than 100	Older than 101

Dates from this study use EU or LU ESR dates combined with all other dating information and are reported as 95% probability ranges.

Table 5
Chronologies for Amud

Hominid provenance	Valladas et al. (1999) (ka)	Rink et al. (2001) mean for layer (ka)	Luminescence with EU ESR (this study) (ka)	Luminescence with LU ESR (this study) (ka)
B_1	70–50 for all three layers	53 ± 7	60–47	65–49
B_2		61 ± 9	64–52	69–56
B_4		70 ± 11	127–59	128–64

Dates from this study use EU or LU ESR dates combined with all other dating information and are reported as 95% probability ranges.

Table 6
Chronologies for Kebara

	Valladas et al. (1987) with 1σ errors (ka)	Schwarcz et al. (1989) with 1σ errors (ka)	Luminescence and EU ESR (this study) (ka)	Luminescence and LU ESR (this study) (ka)
Layer IX	58.4 ± 4.0		61–55	62–55
Layer X	61.6 ± 3.6	60 ± 6 (EU) 64 ± 6 (LU)	62–56	63–57
Layer XII	59.9 ± 3.5		Older than 58	Older than 58

Dates from this study use EU or LU ESR dates combined with all other dating information and are reported as 95% probability ranges.

Table 7
Chronologies for Skhul

Hominid	Date with EU ESR (ka)	Date with LU ESR (ka)
Skhul IX, associated with ESR sample 1057	164–103	173–106
Skhul V, associated with ESR sample 1058	92–59	115–71
All other hominids	154–36	158–43

Dates from this study use EU or LU ESR dates combined with all other dating information and are reported as 95% probability ranges.

Table 8
Chronologies for Tabun

Layer	Grün and Stringer (2000)			Mercier and Valladas (2003)	This study				
	EU	LU	US-ESR		TL only	EU ESR only	LU ESR only	TL + EU ESR	TL + LU ESR
B	102 ± 17	122 ± 16	104			123–63	157–59	128–58	147–64
C	120 ± 16	140 ± 21	135	165 ± 16	198–116	143–107	192–134	169–114	193–135
Ea	176 ± 22	213 ± 32	208	267 ± 22, 264 ± 28	292–223	190–153	221–194	212–196	240–219
Eb	180 ± 32	195 ± 37		324 ± 31	310–268	198–174	228–200	216–199	257–226

Dates from this study use the stated set of dates combined with all other dating information and are reported as 95% probability ranges for fossils attributed to Garrod's layers.

Table 9

Summary of dates and comparisons with previous chronological schemes

Site	Type of date range	Minimum age (ka)	Maximum age (ka)	Stringer (2002)	Thorne and Wolpoff (2003)	Bräuer et al. (1997)
Kabwe	u	490*	1780	350–300	m Mid Pl	265
Olduvai OH 23	p	490*	780*			
Elandsfontein	u	318	791			
Kapthurin KNM-BK 63–67, KNM-BK 8518	m	501	547			
Wadi Dagadle	u	100	900			
Tighenif (Ternifine)	u	116	780	750–700	e Mid Pl	700
Kebibat (Rabat)	u	116	780			250
Ain Marouf	u	116	780			
Nadouiyeh	u	116	780			
Ileret (Guomde)	p	180	795	200–150		280/300
Eliye Springs	u	11	Unknown			200
Melka Konture (Garba III)	u	10	780			
Lainyamok	m	328	393			
Bodo	u	490*	600	650–600	e Mid Pl	600
Salé, Sidi Abderahman, and Thomas Quarries	u	190	525	500–450		400
Laetoli LH 18	p	121	490*		l Mid Pl	170
Eyasi + Mumba	p	118	490*			300/120
Ndutu	p	52	490*		m Mid Pl	400
Olduvai OH 11	p	52	490*			
Florisbad	m	189	329	about 250	l Mid Pl	260
Tabun (Layer Eb)	m	268	310			
Zuttiyeh	u	122	Unknown		l Mid Pl	
Tabun (Layer Ea)	m	223	292			
Mumbwa (Unit XII)	m	149	220			
Mumbwa (Unit X)	m	138	204			
Border Cave (BC1 + BC2 if from 5BS)	m	152	171			
Herto	m	150	161			
Tabun (Layer C)	m	116	198			
Omo Kibish	p	98	192	150–100	e Upp Pl	130/170
Skhul (Skhul IX)	m	106	173		e Upp Pl	

Jebel Irhoud	u	116	150	175–125		190
Klasies River Mouth (LBS)	m	101	Unknown			125
Mumbwa (Unit VII)	m	75	148			
Singa	u	129	Unknown			150
Sea Harvest	u	74	128			
Skhul (Skhul I–IV, VI–VIII, X)	m	43	158	120–100	e Upp Pl	
Amud (Layer B4)	m	64	128			
Tabun (Layer B)	m	63	123	100–90		
Skhul (Skhul V)	m	71	115	120–100	e Upp Pl	
Qafzeh (Q3 and Q6)	m	88	97	120–100	e Upp Pl	
Qafzeh (Layer XVII)	m	87	95	120–100	e Upp Pl	
Aduma	u	80	100			
Die Kelders (Layer 14)	m	78	Unknown			70
Klasies River Mouth (SAS)	m	64	104	100–90	e Upp Pl	90
Border Cave (BC1 + BC2 if from 4BS)	m	71	91			90
Die Kelders (Layer 11)	m	73	85			70
Border Cave (BC3)	m	66	90			90
Die Kelders (Layer 10)	m	72	83			70
Blombos	m	69	Unknown			
Kebara (Layer XII)	m	58	Unknown			
Porc Epic	u	11	136			70
Kabua	u	0	136			
Equus Cave (most likely)	u	24	115			
Shanidar	u	50	Unknown			
Border Cave (BC5)	m	61	72			90
Amud (Layer B2)	m	56	69			
Die Kelders (Layer 4/5 + 6)	m	48	72			
Kebara (Layer X)	m	57	63	60–50	m Upp Pl	
Kebara (Layer IX)	m	55	62	60–50	m Upp Pl	
Amud (Layer B1)	m	49	65	60–50		
Taramsa	m	41	73	60–50		
Klasies River Mouth (HP)	m	47	60			
Klasies River Mouth (WS)	m	Unknown	71			
Mugharet el Aliya (LU ESR)	m	27	57			
Klasies River Mouth (MSA3)	m	Unknown	52			
Dar es Soltane	u	11	35		m Upp Pl	90

For sites with very similar chronologies based on EU-ESR and LU-ESR dates, the LU chronology is listed. These are Skhul, Klasies River Mouth, Amud, Kebara, and Mugharet el Aliya. The TL chronology is shown for Tabun. Where the possible dates are constrained by ages with uncertainties, the two-standard-deviation limit of the age has been taken. All dates in this table are rounded to the nearest 1 ka. Dates marked * are dependent on the choice of long or short chronology for Olduvai; the more likely short chronology dates are shown. The dates derived from Figure 3 in Stringer (2002) are approximate. The midpoint dates from Figure 1 in Bräuer et al. (1997) are given without the original error bars of ±10 ka. Abbreviations are as follows: **u** = a lack of quantitative dating information, **p** = partially quantified dating information, **m** = the stated range is a 95% probability range from a statistical model, **e** = early, **m** = middle, **l** = late, **Mid Pl** = middle Pleistocene, **Upp Pl** = upper Pleistocene.

Figure captions

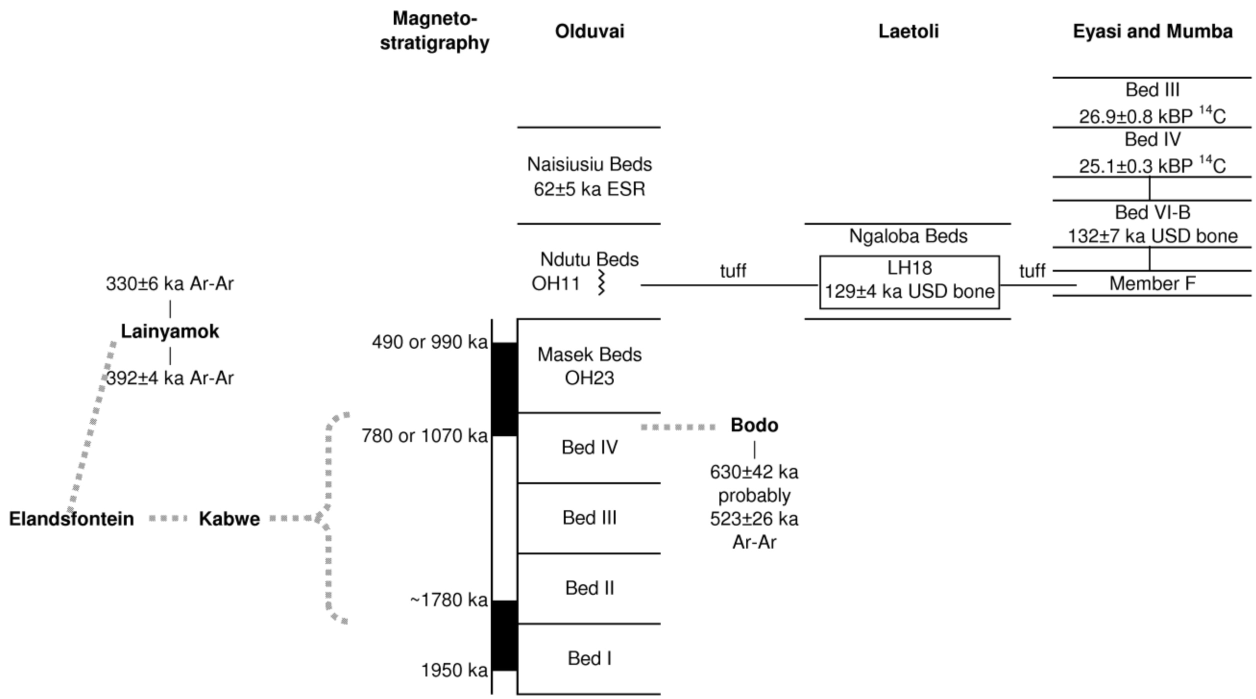
Figure 1. Stratigraphic and faunal correlations with the sequence at Olduvai. Dotted gray lines represent faunal correlations; the magnetostratigraphic column is represented with black for normal polarity and white of reversed polarity. See text for details and references.

Figure 2. Schematic stratigraphy of Klasies River Mouth. The stratigraphic units are shown, with sample numbers of dated materials. Numbers starting with "UW" are luminescence samples from Feathers (2002), those starting with "U" are uranium-series dates from Vogel (2001), and those without an initial letter are ESR dates from Grün et al. (1990b). Dates with sample numbers shown in square brackets [ ] were not included in the calculations (see text).

Figure 3. Summary of dates deduced for "earlier" hominids, with most likely ages older than 200 ka. Where chronologies based on EU and LU ESR differ only slightly, the LU chronology is shown, as in Table 9. Two chronologies are shown for Tabun, with solid lines for the TL-only chronology and dotted lines for the EU-ESR-only chronology. Sites marked * are dependent for their upper or lower limit on the assignment of a date to the magnetic reversal in the Masek Beds. As plotted, the more likely date of 490 ka has been taken, but the 990 ka date cannot be excluded. The ranges marked with a question mark are not fully quantified in some way—see the text for the details of each one.

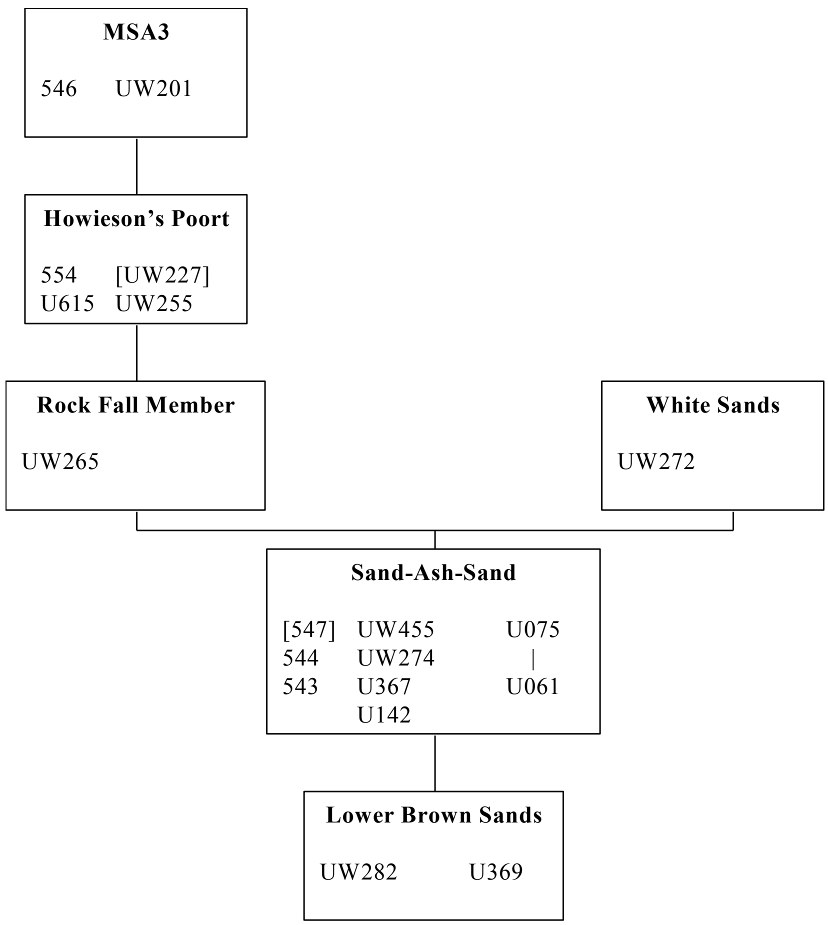
Figure 4. Summary of dates deduced for "later" hominids, with most likely ages younger than 200 ka. Different line styles and the question marks have the same meaning as in Figure 3.

Figure 1



Magneto-stratigraphy
Olduvai
Laetoli
Eyasi and Mumba
Bed III
26.9±0.8 kBP 14C
Bed IV
25.1±0.3 kBP 14C
Naisiusiu Beds
62±5 ka ESR
Bed VI-B
132±7 ka USD bone
Ngaloba Beds
Ndutu Beds
OH11
tuff
LH18
129±4 ka USD bone
tuff
Member F
330±6 ka Ar-Ar
Lainyamok
392±4 ka Ar-Ar
490 or 990 ka
Masek Beds
OH23
780 or 1070 ka
Bed IV
Bodo
630±42 ka
probably
523±26 ka
Ar-Ar
Elandsfontein
Kabwe
Bed III
~1780 ka
Bed II
1950 ka
Bed I

Figure 2



MSA3
546 UW201
Howieson's Poort
554 [UW227]
U615 UW255
Rock Fall Member
UW265
White Sands
UW272
Sand-Ash-Sand
[547] UW455 U075
544 UW274 |
543 U367 U061
U142
Lower Brown Sands
UW282 U369

Figure 3

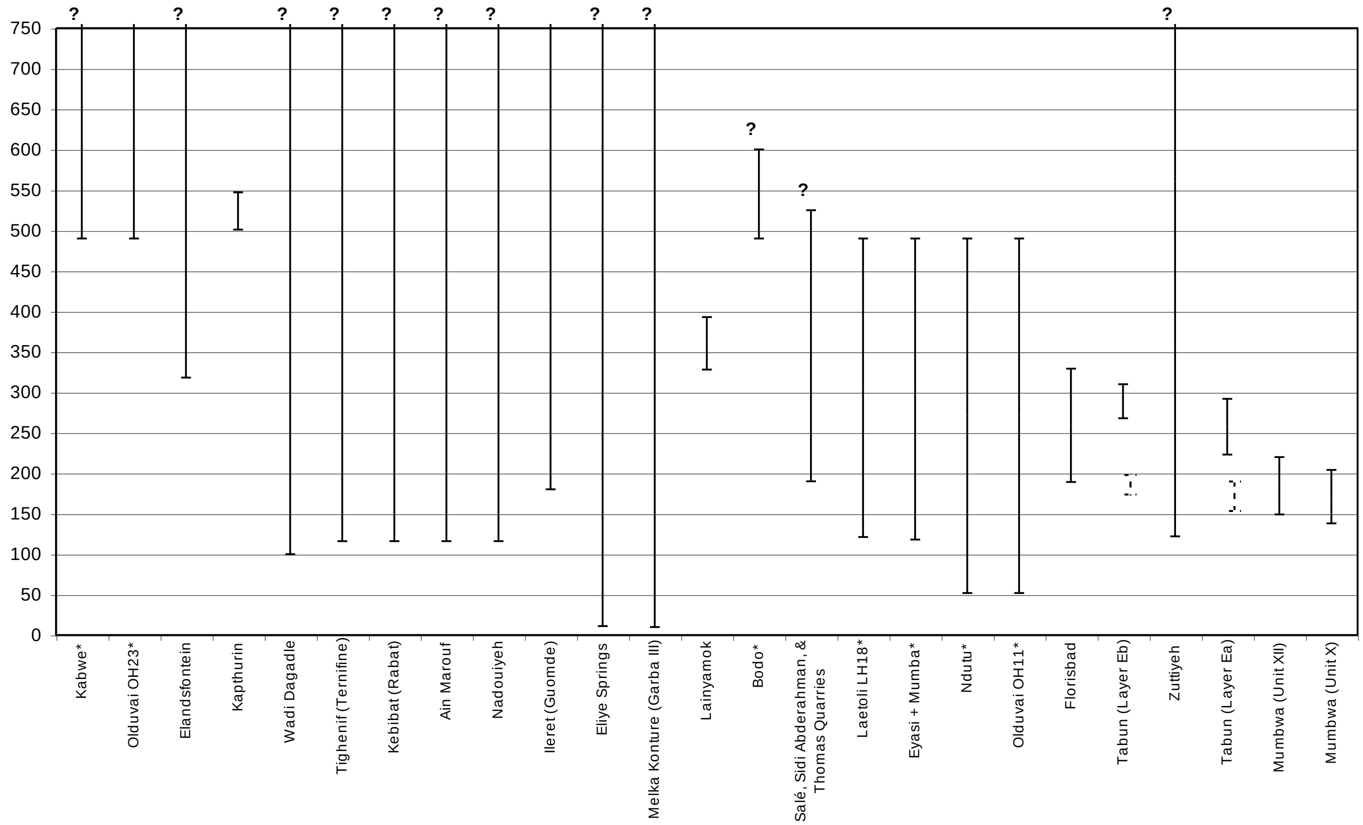
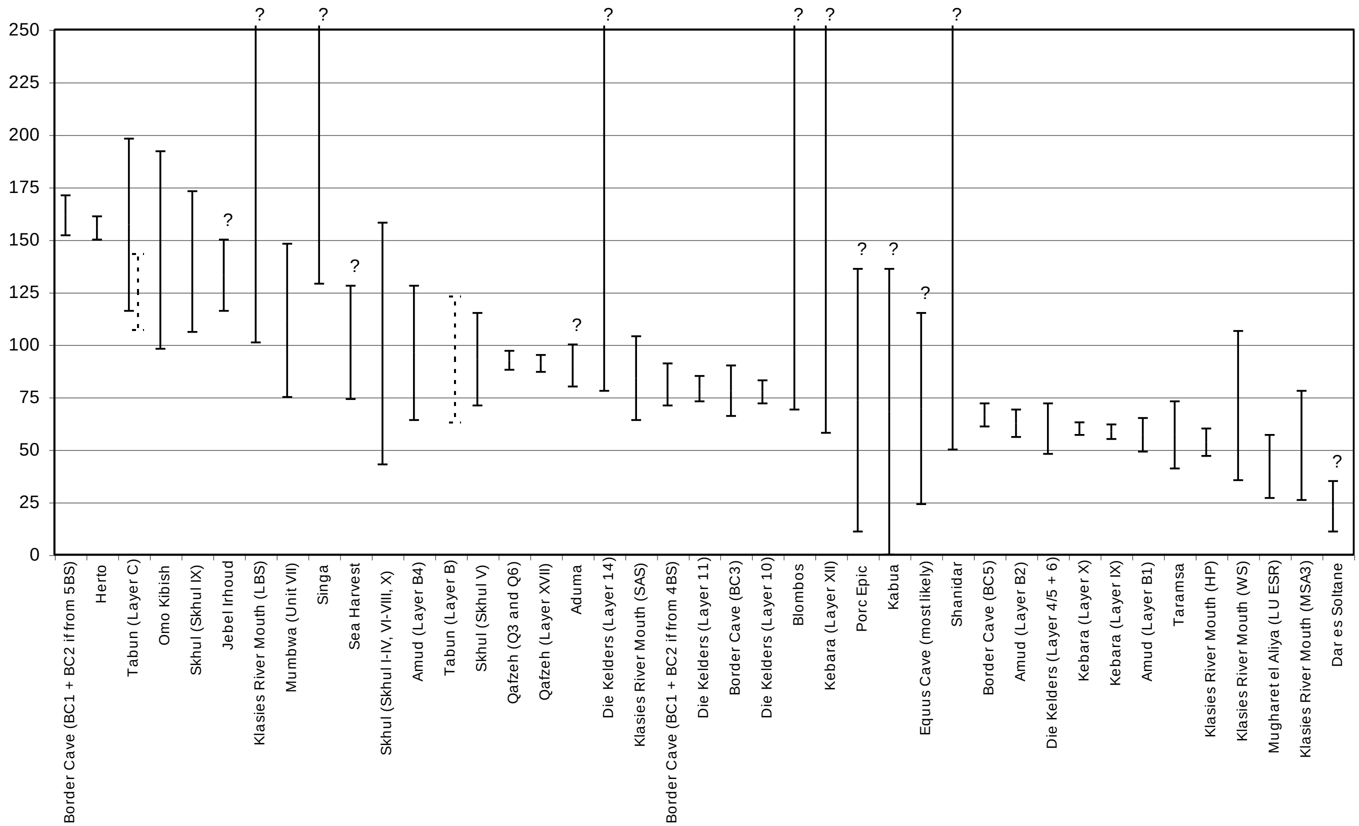

750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
?
Kabwe*
Olduvai OH23*
Elandsfontein
Kapthurin
Wadi Dagadle
Tighenif (Ternifine)
Kebibat (Rabat)
Ain Marouf
Nadouiyeh
Ileret (Guomde)
Eliye Springs
Melka Konture (Garba III)
Lainyamok
Bodo*
Salé, Sidi Abderahman, & Thomas Quarries
Laetoli LH18*
Eyasi + Mumba*
Ndutu*
Olduvai OH11*
Florisbad
Tabun (Layer Eb)
Zuttiyeh
Tabun (Layer Ea)
Mumbwa (Unit XII)
Mumbwa (Unit X)

Figure 4



250
225
200
175
150
125
100
75
50
25
0
?
Border Cave (BC1 + BC2 if from 5BS)
Herto
Tabun (Layer C)
Omo Kibish
Skhul (Skhul IX)
Jebel Irhoud
Klasies River Mouth (LBS)
Mumbwa (Unit VII)
Singa
Sea Harvest
Skhul (Skhul I-IV, VI-VIII, X)
Amud (Layer B4)
Tabun (Layer B)
Skhul (Skhul V)
Qafzeh (Q3 and Q6)
Qafzeh (Layer XVII)
Aduma
Die Kelders (Layer 14)
Klasies River Mouth (SAS)
Border Cave (BC1 + BC2 if from 4BS)
Die Kelders (Layer 11)
Border Cave (BC3)
Die Kelders (Layer 10)
Blombos
Kebara (Layer XII)
Porc Epic
Kabua
Equus Cave (most likely)
Shanidar
Border Cave (BC5)
Amud (Layer B2)
Die Kelders (Layer 4/5 + 6)
Kebara (Layer X)
Kebara (Layer IX)
Amud (Layer B1)
Taramsa
Klasies River Mouth (HP)
Klasies River Mouth (WS)
Mugharet el Aliya (LU ESR)
Klasies River Mouth (MSA3)
Dar es Soltane